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THERMOMECHANICAL PROCESSING AND TEXTURE DEVELOPMENT IN Ni-Cr-Mo AND Mn-Mo-B ARMOR STEELS

April 1984

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FINAL REPORT

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Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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Thermomechanical Processing and Texture Development in Ni-Cr-Mo and Mn-Mo-B Armor Steels

October 1983

by Hsun Hu

United States Steel Corporation
Research Laboratory
Monroeville, Pennsylvania

Final Technical Report
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Foreword

This report was prepared by the Research Laboratory of United States Steel Corporation under U.S. Army Contract No. DAAG46-82-C-0054. The contract was administered by the U.S. Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, Anthone Zarkades - Contracting Officer's Representative. This is a final report and covers work conducted from August 10, 1982, to August 9, 1983.

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Thermomechanical Processing and Texture
Development in Ni-Cr-Mo and Mn-Mo-B Armor Steels

by

Hsun Hu

Abstract

The purpose and scope of the present research were to produce a strong (112) + (111) texture in the quenched and tempered plates of the Ni-Cr-Mo and Mn-Mo-B conventional armor steels by appropriate thermomechanical processing and to study its effect on the mechanical and ballistic properties of the plates. Also, the effect of carbon content above 0.40 percent on the ballistic properties of textured 5Ni-steel armor was to be investigated.

Results indicated that a strong (112) + (111) texture could be produced in plates of both armor steels. Because of the relatively low hardenabilities of these steels, particularly the Ni-Cr-Mo steel, ferrite formation could not be prevented in the on-line quenched plates. The ballistic test results were widely scattered. For optimum development of the (112) + (111) texture in the martensite, studies involving nearly isothermal rolling at a suitable temperature are recommended.

The effect of increasing carbon of the 5Ni steel to 0.45 or 0.47 percent was to increase slightly the hardness and the V_{50} ballistic limit of the textured armor plates. With the higher carbon content, the tempering time appeared to influence the hardness, and the ballistic limit, to a greater degree than for the lower carbon 5Ni steel. Studies aimed at lowering the alloy content of the 5Ni steels are recommended.

Introduction

The effect of crystallographic texture on the mechanical and ballistic properties of high-hardness armor of the 5Ni-Si-Cu-Mo steel has been studied extensively at the U. S. Steel Research Laboratory for the past eight or nine years.[1)*] It was shown that by producing a strong (112) + (111) texture in the quenched and tempered plate, the V_{50} ballistic limit and some other mechanical properties were improved substantially.[2-6)] These studies were conducted mostly with 0.5-inch-thick plates. Additional studies showed that the same texture could be produced in plates of lighter gages ranging from 7/16 to 1/16 inch** thick,[7-9)] including the 1/4-inch-thick full-size plates processed on production mills in scaled-up trials. Similar improvements in the ballistic properties were obtained in these light-gage textured armor plates.[10)]

With these encouraging results, a commercial trial production program for producing full-size plates of textured armor with various thicknesses ranging from 2 inches to 3/16 inch, from two 87-ton heats of the 5Ni steel, was started in April 1982 at the Homestead plant of Mon Valley Works (contract No. DAAG46-82-C-0029). During this past year, work has been conducted on the 2-inch-thick plates, which were considered most difficult to produce in many respects for high-hardness armor.

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* See References.

** The 1/16-inch thickness was obtained by grinding. The smallest thickness of the plate that was processed in the laboratory for textured armor was ~1/8 inch thick.

However, the results have been more than encouraging; complete success was obtained several times. With these experiences, a satisfying conclusion of this trial production program is anticipated.

On the other hand, to further advance research in this area, we have undertaken a program to study the possibility of producing the same kind of texture in the quenched and tempered plates of the conventional armor steels. Hopefully, similar improvements of the properties over the conventional armor may be obtained.

Under the present contract, the scope of research included three parts as follows: (1) The development of a strong (112) + (111) texture in the conventional Ni-Cr-Mo high-hardness armor (the A-46100B grade) by appropriate thermomechanical processing, and its effects on mechanical and ballistic properties. (2) Similar studies for the conventional Mn-Mo-B low-hardness armor (the A-12560D grade). Both of these two grades of conventional armor have been produced routinely at the U. S. Steel Homestead plant for many years. By the introduction of a strong texture in these armor plates, a direct comparison of the properties of textured armor with those of conventional armor plates can be obtained. In addition to the above studies, the current contract program also includes, as a supplemental investigation, (3) the effect of increasing carbon to higher than 0.40 but below 0.50 percent on the ballistic properties of the textured plates of the 5Ni-Si-Cu-Mo armor steel. The present report describes in detail the results of these studies and gives recommendations for future work.

Research Part I: Ni-Cr-Mo and Mn-Mo-B Steels

Materials and Experiments

Steel Composition and Ingot Dimensions

Two 500-pound (227 kg) heats, one for each steel, were melted and cast in vacuum into two ingots 7 by 12 by 24 inches (180 by 305 by 610 mm). Results of ladle and check analyses are shown in Table I. The chemical compositions of these two heats were within the nominal specifications of the two steels and were considered satisfactory for the proposed investigations.

Preliminary Hot Rolling and Slab Preparation

These two ingots were subsequently reheated in a preheating furnace to 2250°F (1232°C) and soaked at temperature for 2 hours for preliminary hot rolling to slabs of predetermined thicknesses. The ingot was first rolled from 7 to 5.5 inches (180 to 140 mm) thick, and a piece of about 10 inches (254 mm) in length was torch-cut from the bottom end of the ingot. The cutoff piece identified as Slab D, was air-cooled to room temperature. The remaining slab was reheated in the furnace for about 20 minutes to restore the temperature, and was then further rolled from 5.5 to 2.75 inches (140 to 70 mm) thick. A piece of about 10 inches (254 mm) long was again torch-cut from the previous cut end of the slab, and was similarly cooled in air to room temperature. This cutoff piece was identified as Slab C. The remaining slab was reheated in the furnace for about 15 minutes to restore the temperature after which further rolling was conducted to reduce the slab thickness from 2.75 to 1.40 inches (70 to 36 mm). Then, a piece about 26 inches (660 mm) in length was

torch-cut and air-cooled to room temperature. This cutoff piece, 1.40 inches or 36 mm thick, was identified as Slab B. The remaining slab was again reheated in furnace for about 15 minutes to restore the temperature, then rolled further to 1.0 inch (~25 mm) thick, and cooled in air. This last piece was, accordingly, identified as Slab A.

The preliminary hot rolling, as described above, thus provided slabs of four thicknesses for the Ni-Cr-Mo and the Mn-Mo-B steels. The 5.5-inch-thick material (Slab D) was intended for final rolling to 1/2-inch- (~13 mm) thick textured armor by ~90 percent reduction. The 2.75-inch-thick material (Slab C), similarly, was for rolling to 1/4-inch- (6.4 mm) thick textured armor by the same amount of rolling reduction (~90%). The 1.40-inch-thick material (Slab B) was for final rolling to 1/2-inch-thick textured armor with a lower total reduction of only about 60 percent (actually ~64%). The 1.0-inch-thick material (Slab A) was to be used as small-block specimens, 1.0 by 1.0 by 0.75 inch (~25 by 25 by 19 mm), for providing basic information on concurrent recrystallization during hot rolling of the austenite, the texture behavior of these two steels in thermomechanical processing, and the transformation characteristics of the highly deformed austenite at some selected temperatures.

In preparation for final rolling, these slabs were subsequently cut along the centerline of the width into two halves, each being 6 inches (152 mm) wide. For temperature control in final rolling, a hole 5/32 inch (~4 mm) in diameter was drilled

into each of the slab pieces (except the 1.0-inch-thick material, which was to be used for the small-block specimens) on the centerline-cut face to approximately the geometric center of the piece for accommodating a thermocouple during final rolling.

Characteristics of the Steels in Thermomechanical Processing

A number of small-block specimens, 1.0 by 1.0 by 0.75 inch thick (~25 by 25 by 19 mm thick) were machined from the 1-inch-thick slab (Slab A) of the two steels. A hole 1/8 inch (3.2 mm) diameter was drilled from the side face to the geometric center of the block for accommodating a thermocouple in the specimen. The thermocouple sheath tube was used as a handle for manipulating the specimen in rolling and heat treating, while the temperature of the specimen was recorded continuously during the experiment.

Recrystallization Tendency and Texture Behavior in Isothermally Rolled Specimens. With a radiant-tube furnace mounted close to and on each side of the laboratory rolling mill, the specimen can be rolled nearly isothermally by reversing passes through the mill with brief reheatings in the tube furnace to restore the temperature. The small-block specimens were first austenitized in a nearby muffle furnace at 1700°F (927°C) for 15 minutes, then transferred to the tube furnace set at a desired temperature for isothermal rolling. The specimen was rolled 80 percent from 0.75 to 0.15 inch (1.9 to 3.8 mm) thick in 14 passes, with a reduction of approximately 11 percent per pass, and was quenched immediately in water after the last pass.

The microstructure of the quenched specimen was examined on a longitudinal section, and the diamond pyramid hardness (DPH) was determined by taking the average of five measurements across the thickness of the specimen. The crystallographic texture of each specimen was examined by determining the (110) pole figure for the midthickness plane, using MoK_{α} radiation and the Schulz reflection method.[11] A summary of the observed hardness and the microstructural and textural features of the isothermally rolled specimens is presented in Table II and Table III for the Ni-Cr-Mo (the A-46100B grade) and the Mn-Mo-B (the A-12560D grade) armor steels, respectively.

As can be determined from the information summarized in Table II and Table III, the appropriate hot-rolling temperatures for developing a strong (112) + (111) type texture in the quenched and tempered plates should be within the range of 1550 to 1450°F (843 to 788°C) for both the Ni-Cr-Mo and Mn-Mo-B steels. For the latter, the lower limit could be extended to 1400°F (760°C). Rolling at temperatures above this range caused recrystallization of the austenite, resulting in a decrease of the intensity of the (112) + (111) texture. Rolling at temperatures below this range causes ferrite formation in the austenite, which leads to a lower hardness of the quenched specimen.

As a typical example, the (110) pole figures of the isothermally rolled specimens of the Ni-Cr-Mo and Mn-Mo-B steels are shown in Figure 1. These specimens were rolled at 1550°F (843°C) to 80 percent reduction, and were immediately quenched after the last pass. These pole figures are quite similar to

those observed for the 5Ni steel quenched from deformed austenite after 80 or 90 percent straightaway rolling, indicating a strong (112) + (111) texture.

Transformation Kinetics of Deformed Austenite at Selected Temperatures. To obtain some information on the kinetics of phase transformations in highly deformed austenite of the two steels, the same small-block specimens were used. With the inserted thermocouple, the specimen was first isothermally rolled then heat treated immediately at a lower temperature for isothermal transformation. Following exactly the procedures employed previously for isothermal rolling, the specimens were first austenized at 1750°F (927°C) for 15 minutes, isothermally rolled at 1550°F (843°C, an appropriate temperature for producing a strongly textured armor plate) to ~70 percent reduction,* transferred immediately to a lead bath at a selected temperature, and held at that temperature for various lengths of time, then quenched in water.

Three subcritical temperatures were selected for the present studies: (1) 1200°F (649°C), a temperature which corresponds approximately to the "nose" of ferrite formation in the isothermal transformation diagram of steels having comparable compositions;[12] (2) 1050°F (566°C), which corresponds roughly to the temperature in the "bay" area between ferrite and upper

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* During earlier experiments on isothermal rolling, thermocouple breakage occurred frequently in the last pass to complete the 80 percent reduction. To avoid such difficulty, the amount of total rolling reduction was reduced to ~70 percent to facilitate the immediately following treatment for isothermal transformation of the specimen.

bainite transformations; and (3) 900°F (482°C), a temperature which corresponds roughly to the nose of upper bainite transformation. Various lengths of time at each temperature were employed.

The microstructures of the quenched specimens were examined on the longitudinal cross section. The amount of the isothermally transformed phase was estimated under the microscope and rechecked by linear intercepts on the photomicrographs taken of the extreme specimens (specimens heat treated for the shortest and the longest times at each temperature). The microstructural features and the hardness measured from the metallographically prepared section of the specimens are summarized in Table IV for the Ni-Cr-Mo and Table V for the Mn-Mo-B armor steels.

By comparing the observed features summarized in Table IV and Table V, it becomes quite obvious that the ferrite transformation from the austenite in the Mn-Mo-B steel was much more retarded than in the Ni-Cr-Mo steel probably because of the presence of boron. The retarding effect by boron was also indicated by the amounts of upper bainite formation, although to a lesser degree, in these two steels. These observations are consistent with the known effect of boron in increasing the hardenability of hypoeutectoid steels by retarding the nucleation of proeutectoid ferrite at austenite grain boundaries.[13] The somewhat lesser retarding effect for upper bainite transformation is also consistent with the above interpretation because upper bainite is known to be nucleated by ferrite.[14]

As can be seen from Table IV and Table V, the rates of bainite transformation in rolled specimens of the Ni-Cr-Mo and Mn-Mo-B conventional armor steels were fairly fast. In texture rolling of armor plates, a drastic quench would probably have to be employed if the formation of bainite is largely to be avoided. For thick plates, it may not be possible to prevent the formation of bainite because of their slower cooling rates.

Final Hot Rolling to Textured Armor Plates

For final rolling, the slab pieces were preheated to 1700°F (927°C) and held at temperature for 2 hours. Based on the information obtained from basic studies on the recrystallization tendency and texture behavior of these two steels, it was intended to start rolling at about 1600°F (899°C) and to finish rolling at about 1450 to 1400°F (788 to 760°C) with a reduction per pass in the range of 10 to 15 percent. The rolled plate was to be quenched immediately after the final pass by on-line water-spray quenching to room temperature.

The actual processing conditions in final rolling each of the slab pieces are summarized in Table VI (for the Ni-Cr-Mo steel) and Table VII (for the Mn-Mo-B steel). As shown by the recorded data in these tables, there were considerable variations among the temperatures of the slab pieces before rolling was started (i.e., at pass no. zero). For example, in Table VI, the lowest temperature of the reheated slab piece (Plate B-1) was 1570°F (854°C), whereas the highest temperature observed for other slab pieces (Plate C-2 and Plate D-1) was 1770°F (966°C). Similarly, in Table VII, the lowest and highest temperatures of

the slab pieces (Plate B-1 and Plate D-1) were 1625 and 1800°F (885 and 982°C). Variations of this magnitude (175 to 200°F) in the preheating furnace were not experienced in previous practices. These were possibly due to (1) the position of the slab piece in the preheating furnace, (2) the thickness of the slab piece, and (3) the variation in time from discharging the slab piece, moving the piece to the front of the rolling mill, and inserting the thermocouple into the hole in the slab piece. The finish-rolling temperatures for the 1/4-inch-thick plates (the Plate C's) were appreciably lower than intended, because of a faster rate heat loss for the thinner plates. Occasional delays in the manual feeding of the mill for the passes also increased the heat loss of the piece.

The quenched plates were subsequently cut into 12-inch-long pieces. These 6- by 12-inch plates were then tempered either at 350 or 1100°F (177 or 593°C) for 1 hour to correspond either the high-hardness armor (A-46100B grade of the Ni-Cr-Mo steel) or the low-hardness armor (A-12560D grade of the Mn-Mo-B steel) specifications.

It should be noted that, in all previous investigations, the plates were rolled 90 percent reduction to thicknesses somewhat greater than the final thicknesses desired. The tempered plates were finally surface ground to remove scale and decarburized layer and to the exact gage thickness desired. In the present investigation, the plates were rolled to the final gage thickness desired, and no surface grinding was applied to the tempered plates. These procedures were adopted upon

considerations of the following: (1) the thin decarburized layers would not significantly affect the V_{50} ballistic limit of the plate; and (2) by eliminating the surface grinding operation, considerable time and labor could be saved for other purposes in this study.

Results and Discussion

Hardness and Microstructure of the Plates

The hardness of the plates in the as-quenched and tempered conditions were measured on the cross sections of the plates prepared for microstructure examination. As usual, five diamond pyramid hardness (DPH) measurements were made across the thickness of the plate, and the average value was taken. These hardness values and their equivalent HRC numbers are shown in Table VIII for both Ni-Cr-Mo and Mn-Mo-B steels. The hardness values after tempering at 350°F (177°C) for 1 hour (as required for the high-hardness armor of the Ni-Cr-Mo steel), and at 1100°F (593°C) for 1 hour (as required for the low-hardness armor of the Mn-Mo-B steel), were very close to the specification requirements (HRC 52 for the high-hardness armor, and HRC 37 for the low-hardness armor), except that the 1/4-inch-thick C-plates of the Ni-Cr-Mo steel had a hardness about 4 points lower than the specification. As mentioned earlier, the hardenability of this steel was fairly low, consequently, some ferrite could have been formed from the austenite during air cooling of the plate prior to quenching. This would be particularly likely to occur in the thin-gage plates, because the rate of heat losses in these plates during rolling was fairly rapid. It can also be noted from

Table VIII that the difference in hardness between the as-quenched and the 350°F tempered plates was very small. This could be an indication that with some ferrite formation the residual stresses in the quenched plate would be correspondingly less than those in a fully quench-hardened plate with 100 percent martensite.

The microstructure of the plate was examined on the longitudinal and transverse cross sections of the plate. The metallurgical features of the microstructure are briefly summarized in Table IX for both the Ni-Cr-Mo and the Mn-Mo-B steels after respective tempering treatments. Optical photomicrographs showing representative microstructures of the plates of the Ni-Cr-Mo steel are shown in Figure 2, and those of the corresponding plates of the Mn-Mo-B steel are shown in Figure 3. The observation of considerable amount of ferrite formation in the thin-gage plate of the Ni-Cr-Mo steel confirmed the lack of hardenability of this steel upon delayed quenching.

Crystallographic Texture of the Plates

The texture of the plate was examined by determining X-ray pole figures from {110} reflections at the midthickness of the plate. For all the plates processed in this investigation, the texture was the (112) + (111) type. It is, therefore, unnecessary to present all these pole figures for all the plates rolled. For brevity, only the (110) pole figures of the B1, C1, and D1 plates of each of the two steels are reproduced. These are shown in Figure 4 for the Ni-Cr-Mo steel plates, and in Figure 5 for the Mn-Mo-B steel plates. However, to ensure complete

documentation of the experimental data, the mean intensity maxima of the pole figures of all the plates are summarized in Table X. As these data show, the texture intensities of the B-plates were significantly lower than those of the C- or D-plates,* because the B-plates were rolled 60 percent (actually ~64%), whereas the C- and D-plates, 90 percent (actually ~91%). The very strong textures produced in the Mn-Mo-B armor plates (as high as ~9 times random) were particularly encouraging. It may be worthwhile to examine textured armor of this steel at both low-hardness and high-hardness conditions by tempering at both high and low tempering temperatures (for example, 350 and 1100°F). Without the occurrence of recrystallization in tempering, there should be no essential change in the crystallographic texture of the plate. However, the microstructure of the plates would be significantly different between plates tempered at considerably different temperatures, such as the size and distribution of the precipitated carbides, as well as the density of dislocations and the subgrain structures of the tempered martensites. These would certainly influence the mechanical and the ballistic properties of the plates.

In-Plane Tensile Properties

The in-plane tensile properties of the plates were determined by testing specimens prepared along three directions in the plane of the plate. These were the longitudinal (L), the diagonal (D) (i.e., 45° from the rolling and the transverse

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* For reasons unclear at present, the texture intensity of the plate D2 of the Ni-Cr-Mo steel was lower than expected.

directions), and the transverse (T) directions. For the 1/2-inch-thick B- and D-plates, the tension specimens were 0.25 inch (6.3 mm) in diameter and 1 inch (25.4 mm) in gage length. For the 1/4-inch-thick C-plates, the specimens were 0.125 inch (3.2 mm) in diameter and 0.5 inch (12.7 mm) in gage length. Duplicate specimens were tested and the averaged testing data are summarized in Table XI.

To show that the in-plane properties of these plates were anisotropic, the ratio of the properties in the transverse direction to those in the longitudinal direction (T/L) was indicated in the tabulation. For the Ni-Cr-Mo plates, these parameters indicate somewhat lower anisotropy in comparison with the 5Ni textured armor plates rolled to high reductions, for example, rolled 80 or 90 percent to 0.5 inch thick, quenched, and tempered at 350°F for 1 hour (see Table IV in Ref. 6). This appears to be consistent with the intensity of the texture which is correspondingly lower in the present Ni-Cr-Mo plates (Table X). In comparison with 5Ni textured armor, the yield strength and the reduction of area of corresponding plates are comparable. The tensile strength and total elongation, however, are appreciably lower. As obviously known, the 5Ni steel is richer overall in alloy content than the present Ni-Cr-Mo steel. For the Mn-Mo-B plates, there seem to be some inconsistencies in the correlation between anisotropy and the texture intensity of the plates. For example, the T/L ratios of the C-plates indicate lower anisotropies in comparison with the B- or D-plates, whereas the texture intensities of the C-plates, as shown in Table X, were higher.

The reason for this inconsistency is unclear at present. However, nonhomogeneity of the plates, as shown by other observed properties to be presented later, is a possibility.*

<u>Through-Thickness Tensile Properties of Notched Specimens</u>

For high-hardness armor, back spalling of the plate upon high-speed projectile impact is one of the major concerns in evaluating the ballistic performance of the plate. It was suggested[15)] that the resistance to spalling at a constant strain rate could be determined for plates by testing the through-thickness tensile strength under constraint conditions, such as with the sharply notched specimen shown in Figure 6 in which the planar strains $\varepsilon_1 = \varepsilon_2 = 0$. In previous investigations, a qualitative correlation was observed between the through-thickness tensile strength of such notched specimens and the resistance to back spalling of the ballistic tested plates (the higher the through-thickness notched tensile strength the stronger the resistance of the plate to back spalling).[2)] A qualitative correlation was also observed between the through-thickness tensile strength of the notched specimens and the diameter of exit holes of the ballistic-tested plates (the higher the through-thickness notched tensile strength, the smaller the diameter of the exit hole of the tested plate).[16)]

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* The small sample material used for microstructure, texture, and hardness examinations was taken from the central location of the rolled long plate where the control thermocouple was embedded. It was tempered in a small tube or muffle furnace. The rest of the rolled plate was cut into a number of 12-inch-long plates and batch-tempered in a large air furnace. These plates were used for various mechanical and ballistic tests.

Similar tests were conducted on the 0.50-inch-thick plates (the B- and D-plates) of the present two steels. For the 0.25-inch-thick C-plate, such tests could not be made because of its small thickness. Table XII shows the results. As can be noted from these limited data, the Mn-Mo-B steel plates showed little difference in the tensile strength under the notched condition between the B- and D-plates, probably because of their low hardness. For the high-hardness Ni-Cr-Mo plates, the notched tensile strength of D-plate was slightly lower than that of the B-plate. The trend is thus consistent with previous observations on 5Ni steels, that is, the notched tensile strength is lower in the plates rolled to higher reductions. Accordingly, the resistance to back spalling would be expected to be somewhat less for D-plates than for B-plates.

Charpy Impact Properties

The Charpy V-notch impact properties of the plates were determined by testing at room temperature on duplicate specimens prepared along the longitudinal (L), diagonal (D), and transverse (T) directions. For the 0.50-inch-thick B- and D-plates, full-size specimens were used; for the 0.25-inch-thick C-plates, half-size specimens were used and results analyzed on an equivalent energy-area basis (2 X actual impact energy) after the work reported by C. F. Hickey, Jr.[17] The results are shown in Table XIII. In agreement with previous observations[1,2,4] on 5Ni textured armor plates, the impact energy was the highest in the longitudinal, intermediate in the diagonal, and lowest in the transverse directions. For the high-hardness Ni-Cr-Mo plates,

the impact energies were comparable to those of the 5Ni plates control-rolled with declining temperature,[1] but were somewhat lower than the corresponding impact energies of the earlier isothermally rolled plates.[2,4] This is understandable on the basis that, besides the leaner alloy contents of the Ni-Cr-Mo steel, the present plates were actually rolled also with declining temperatures (see Table VI).

The impact energies of the Mn-Mo-B plates were substantially higher than those of the Ni-Cr-Mo plates. This was to be expected because of the high tempering temperature required for the low-hardness armor of this steel.

Ballistic Performance of the Plates

To broaden the preliminary exploration on the ballistic performance of textured armor of these two conventional armor steels, the V_{50} ballistic limits were tested at both high-hardness and low-hardness conditions for each of the steels. In other words, plates of both the Ni-Cr-Mo (normally used as high-hardness armor) and the Mn-Mo-B (normally used as low-hardness armor) steels were each tempered at both low and high temperatures (350 and 1100°F) for ballistic testing. For the 1/2-inch-thick plates, 0.50 caliber AP M2 projectiles were used; whereas for the 1/4-inch-thick plates, 0.30 caliber AP M2 projectiles were used. All tests were conducted with zero-degree obliquity. These V_{50} limits, together with other pertinent information of test plate, are summarized in Table XIV. Results of these tests showed considerable scatter and inconsistency. Even the hardness of some of the plates of the Ni-Cr-Mo steel showed unusually low

values. For example, the D2 plate tempered at 350°F (HRC = 44); and the C1 plate tempered at 1100°F (HRC = 33). The HRC values of the ballistic test plates (Table XIV) were obtained by measurements made on the surface after the plate was spot-ground to remove the surface oxides and the decarburized layer (about 0.010 inch in depth) until a constant hardness value was obtained upon further spot grinding and measuring. Except these two particular plates which showed unusually low hardness values, all the other plates had HRC values quite comparable with those shown in Table VIII. The considerable deviation in hardness of the Ni-Cr-Mo plates indicate that, because of the relatively low hardenability of the steel, the microstructure and property of the rolled and quenched plate may vary significantly from end to end.

The variations in the V_{50} ballistic limit, as determined in the usual manner to represent the critical velocity of the projectile having a 50 percent probability for complete penetration, were even more surprising than the observed variations in hardness. The most astounding example is the difference in the V_{50} ballistic limits observed for C1 and C2 plates of the Mn-Mo-B steel tempered at 350°F. The C2 plate had a lower hardness but a substantially higher V_{50} limit than the C1 plate. To determine whether the microstructures of these two plates were substantially different, specimens were cut from these ballistic-tested plates for metallographic examination, and the hardness across the thickness of the plate was measured. No significant difference in microstructure was observed. The average DPH

across the thickness of the plate was 540 (HRC 51.8) for plate C1, and 557 (HRC 52.8) for plate C2. These hardness values were slightly better correlated with the observed ballistic limits than did the hardness values shown in Table XIV (HRC 52 for C1, and 49 for C2). However, the great difference in V_{50} limits as observed for these plates, namely 1414 fps for C1, and 2042 fps for C2 (see Table XIV) was difficult to rationalize based on results of these metallographic and hardness examinations. A great difference in V_{50} limit was also observed between D1 and D2 plates which had the same hardness after the 350°F tempering treatment.

To ensure that these widely scattered V_{50} limits were not significantly influenced by the surface oxides and decarburized layer material on the plates,* suitable plates were selected for check testing of the V_{50} limits after surface grinding or grit blasting. The results are shown in Table XV. The magnitude and scatter of the V_{50} limits of these plates were largely comparable to those of the plates tested without prior surface grinding or grit blasting. It appeared fairly certain that the presence of a thin layer of oxides and decarburized material on each surface of the plate (total ~0.020 inch thick) did not significantly affect the ballistic performance of the plate.

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* In all earlier investigations, the plates were always surface-ground to remove the oxides and decarburized layer material before ballistic testing.

It has been known that for some armor plates of intermediate hardness (in the range of 400 to 475 BHN or 43 to 50 HRC), ballistic testing may show double V_{50} limits at well-separated critical velocities. This is commonly known as the "shatter gap" in ballistic performance. To check this possible behavior of the present plates, the ballistic testing data were closely examined. Taking $[V_{50}]_1 - [V_{50}]_2 > 150$ fps as a criterion for shatter gap behavior, the results of such ballistic data analyses are shown in Table XVI for the Ni-Cr-Mo steel plates, and Table XVII for the Mn-Mo-B steel plates. As can be seen from these tabulations, the possibility of shatter gap behavior was indicated for plates of both Ni-Cr-Mo and Mn-Mo-B steels tempered at the lower temperature (350°F) when the hardness was in the right range. For plates tempered at the higher temperature (1100°F), no shatter gap behavior was indicated, because the hardness fell below the range where such behavior was mostly obtained.

Even with this possible shatter gap behavior of the plates, the wide scatter of the ballistic limits made a consistent interpretation of the data impossible. A further attempt to improve our understanding of the ballistic results was conducted by examining the as-quenched and the tempered structures in more detail by using transmission electron microscopy on the longitudinal cross sections of the plates. Results of these examinations are described in the following section.

Study of the Substructures by
Transmission Electron Microscopy

The substructures of the plates in conditions of as-quenched, tempered at 350°F for 1 hour, and tempered at 1100°F for 1 hour were examined by transmission electron microscopy. To see the substructure of the heavily rolled plates more clearly, thin foil specimens were prepared parallel to the longitudinal cross section of the plate. As it is known that in heavily rolled materials, the smallest dimension of the substructure cells is in the thickness dimension. Consequently, in transmission electron microscopy, thin foil specimens prepared parallel to the rolling plane do not show clearly defined cell structures because a number of layers of cells are overlapped one upon another in transmission examination.[18] Only plate D1 of the Ni-Cr-Mo and of the Mn-Mo-B steels were examined, using a JEOL 200CX Temscan operated at 200 kV.

Figure 7 shows the microstructure of the D1 plate of the Ni-Cr-Mo steel in the as-quenched condition. In the lath martensite matrix there were areas containing a fair amount of ferrite grains. The size of these ferrite grains were approximately 1.5 μm in diameter. There were fine precipitates, ~10 to 20 nm in diameter, in the ferrite grains. Positive identification of these precipitates could not be obtained because of their small size. Evidence of ε-carbide precipitation in the martensite lath was observed as shown by the micrograph in Figure 9A. This was obviously a consequence of quench aging.

The microstructures of the as-quenched plate of the Mn-Mo-B steel are shown in Figure 8. The martensite laths were

highly dislocated, and in some regions, contained microtwins. Ferrite grains were also observed, but they were considerably smaller in size and in quantity than those in the Ni-Cr-Mo plate. These observations were in essential agreement with the results obtained from optical microscopy described earlier (see Figures 2 and 3, also Table IX). Fine precipitates similar to those present in the Ni-Cr-Mo plate were also detected in the Mn-Mo-B plate.

Except the amount of ferrite, the microstructural features of the plates tempered at 350°F for 1 hour were similar for both steels. Figures 10 and 11 show the microstructures of the Ni-Cr-Mo plate and the Mn-Mo-B plate, respectively, after the 350°F tempering treatment. Little polygonization of the highly dislocated substructure was observed. This low temperature tempering treatment also resulted in the precipitation of ε-carbide in the martensite laths of the Mn-Mo-B plate, Figure 9B.

Figures 12 and 13 show the microstructures of the Ni-Cr-Mo and Mn-Mo-B plates, respectively, after tempering at 1100°F for 1 hour. The microstructural changes in both steels after this tempering treatment were again largely similar. Large, discrete Fe_3C particles were formed on lath boundaries and in ferrite grains. This extensive carbide precipitation and particle growth were also accompanied by extensive recovery of the martensite, which changed from highly dislocated substructure of the martensite laths to well-defined acicular ferrite subgrains.

Summary and Conclusions

The possibility of producing a strong crystallographic texture of the (112) + (111) type in the quenched-and-tempered plate of the Ni-Cr-Mo and the Mn-Mo-B conventional armor steels by thermomechanical processing has been studied. Textured plates having nominal thicknesses of 1/2 and 1/4 inch, and processed by low and high rolling reductions (~60 and 90%, for the purpose of varying the intensity of the texture) were produced and tested. The results can be summarized as follows:

1. The Ni-Cr-Mo steel, in comparison with the Mn-Mo-B steel, has a fairly low hardenability with respect to the formation of ferrite from austenite. However, both steels transformed isothermally to bainite at fairly rapid rates even though the rate for Mn-Mo-B steel was somewhat slower than that of the Ni-Cr-Mo steel. This observed difference in transformation characteristics between these two steels was to be expected, because it is known that boron increases the hardenability of the steel by retarding ferrite nucleation at the austenite grain boundaries.

2. A strong (112) + (111) texture can be produced in the martensite of the quenched plates of both steels by heavy rolling the austenite without recrystallization and by sufficiently rapid quenching immediately following rolling. For the Ni-Cr-Mo steel, the appropriate temperature for texture rolling is in the range of 1550 to 1450°F, and for the Mn-Mo-B steel, in the range of 1550 to 1400°F. Understandably, the thickness of the plate can significantly affect the results.

3. In actual processing of the 1/2- and 1/4-inch-thick plates in the present investigation, the temperature for start-rolling was somewhat higher than the desired upper limit so that rolling could be finished not too far below the desired lower temperature limit. The intention of employing such a rolling schedule with declining temperatures, instead of an approximately isothermal one (possible only for certain plate thicknesses, e.g., >1/2 inch), was to simulate the rolling conditions encountered in commercial practice more closely. It was found that the processed plates of the Ni-Cr-Mo steel had an appreciable quantity of ferrite grains. Trace ferrite was also found in most of the Mn-Mo-B plates.

4. Although the tensile and other mechanical properties of the quenched-and-tempered plates of the two steels showed consistent test results and reasonable anisotropies consistent with the crystallographic texture, the ballistic test results showed wide scatter. No satisfactory explanation for this behavior could be offered at the present time. For some of the plates, the wide scatter of V_{50} ballistic limits may be related to the possible "shatter gap" behavior of their ballistic performance. Whether the presence of ferrite grains in the plate had some influence on the ballistic behavior observed is not clear at this point.

Recommendations for Future Work

Based on the results of the present investigation, it is suggested that the effect of crystallographic texture on the ballistic properties of the Ni-Cr-Mo and Mn-Mo-B conventional

armor steels be further studied with strictly controlled processing conditions. The scope of investigation should be more specific and limited in each investigation so that a better understanding of the results may be obtained. For example, the rolling should be conducted as nearly as possible isothermally, at several temperatures within the desired range for texture development; and the thickness of the plate should be limited to the 1/2-inch thickness only for the initial study. The tempering treatment should also be limited to one temperature so that a concentrated study can be performed.

Research Part II: Higher Carbon 5Ni Steels

Chemical Composition of the Steel (First Heat)

For the higher-carbon 5Ni-Si-Cu-Mo steel, one 500-pound heat was vacuum melted and cast into an ingot, 7 by 12 by 24 inches in dimension. The chemical composition of this first heat (8291-8016), shown by ladle analysis, is given in Table XVIII. The phosphorus content was lower than usual, whereas the sulfur content was higher than usual. It was thought that the ladle analysis might be in error, and that in the future check analysis on the plate the concentration of these two elements may actually be more reasonable. The concentrations of carbon and other alloy elements were considered satisfactory.

Preliminary Hot Rolling of the Ingot (First Heat)

For preliminary hot rolling to slabs, the ingot was hot-charged to a preneating furnace at 2250°F and soaked at temperature for 2 hours. The rolling and torch-cutting procedures were largely the same as for the Ni-Cr-Mo and Mn-Mo-B steels (as described in Research Part I), except that for the 5Ni steel, slabs of three thicknesses were produced. They were 5.50, 2.75, and 1.40 inches thick, and were identified as Slabs C, B, and A, respectively. All these slabs were first cooled in air to about 900°F, then cooled slowly in vermiculite to room temperature to avoid the possible occurrence of hairline cracking as observed in earlier investigations.[16)]

Samples for check analysis of the phosphorus and sulfur contents were taken from the 1.40-inch-thick plate (Slab A) at two locations, one near the centerline, the other near the rim of

the ingot. Results of these check analyses are also shown in Table XVIII. The higher-than-usual sulfur content of this heat was certain.

Because the main purpose of this supplemental study on the 5Ni steel armor was to ascertain the effect of higher carbon on the ballistic properties of the plate, the higher sulfur content of this heat would add another variable to the study. It was decided that a second heat be made to eliminate the uncertainty due to high sulfur content in the steel.

Chemical Composition of the Steel (Second Heat)

A second heat of the higher carbon 5Ni-Si-Cu-Mo steel was made and cast according to the normal procedures with special attention on low sulfur content in the charges. The chemical composition of this second heat (8291-8019) shown by ladle analysis is given in Table XIX. The carbon content of this second heat was slightly lower than that of the first heat, but all the other alloy contents were close to specifications.

Preliminary Hot Rolling of the Ingot (Second Heat)

Following the same procedures, the ingot cast from the second heat was hot rolled to slabs 5.50, 2.70, and 1.40 inches thick. These slabs were similarly identified as Slab A (1.40 inches thick), Slab B (2.75 inches thick), and Slab C (5.50 inches thick).

For final rolling to textured armor plates, the slabs of three different thicknesses (1.40, 2.75, and 5.50 inches, respectively, for Slabs A, B, and C), rolled from the first-heat (8291-8016) and second-heat (8291-8019) ingots, were subsequently

cut along the centerline of the width into two halves, each being 6 inches wide. For temperature monitoring in final rolling, a hole 5/32 inch in diameter was drilled into each of the slab pieces on the centerline-cut face to approximately the geometric center of the slab piece for accommodating a thermocouple for temperature measurements during final rolling.

Final Hot-Rolling to Textured Armor Plates

For the slabs rolled from the second-heat ingot (8291-8019), the two slab pieces of each thickness (produced by cutting along the centerline of the slab width into two halves) were all final-rolled to textured armor plates 1/2 or 1/4 inch in thickness. The final rolling conditions are summarized in Table XX.

To avoid the possibility that minor cracks might develop in the quenched plate of this 5Ni steel having a higher carbon content, the on-line water-spray-quenched plates, 6 inches wide by ~100 inches long, were immediately charged into a furnace at the end of the quenching bed for tempering at 350°F for ~1 hour. The tempering time was actually counted from the time when the last plate was charged into the furnace to the time that the power of the furnace was turned off at the end of 1 hour. The plates were then allowed to cool in the furnace to room temperature. The six slab pieces were rolled in the sequence A1, A2, B1, B2, C1, and C2. Therefore, the residence time for tempering at 350°F was somewhat longer than 1 hour for the earlier plates than for the last one. This time differential is believed to be of negligible significance. These on-line tempered plates

were subsequently cut each into a number of 12-inch-long by 6-inch-wide plates for ballistic testing.

Hardness, Microstructure, and Texture

The hardness, microstructure, and crystallographic texture of the tempered plates were examined in the usual manner as conducted in previous investigations. There were no unusual features significantly different from those observed in the 5Ni steels with nominal 0.40C and similarly processed. The tempered plates showed slightly higher hardness than plates studied in previous investigations. This was obviously due to higher carbon in the present steels. There was a noticeable decrease in hardness when the on-line tempered plates were given additional tempering for 1 hour. This observation indicates that with higher carbon steel the time of tempering appears to influence hardness to a greater degree than with the lower carbon steel. The hardness and texture data of the plates were all presented together with the ballistic testing results in following tabulations.

Ballistic Performance

The relevant data for the on-line tempered plates of the 0.45C, 5Ni steel are shown in Table XXII. The present results indicate that by increasing the carbon content of the 5Ni steel from 0.40 to 0.45 percent, there is a slight increase in the ballistic performance.

Table XXIII shows data for the 0.47C, 5Ni steel armor. The on-line tempered 0.45C, 5Ni plates, after being given an additional hour tempering at 350°F, were also included in the test. The results showed that the hardness and the ballistic

performance decreased noticeably with the additional tempering treatment. This observation indicates that with a higher carbon content, hence a higher as-quenched hardness, the time of tempering can influence the hardness significantly. The ballistic properties of the 0.47C, 5Ni armor plates were quite similar to those of 0.45C, 5Ni plates. The back-spalling and cracking tendencies of the higher carbon 5Ni steel armor appeared to be roughly equal to, or occasionally slightly poorer than, those of the 0.40C, 5Ni steel armor similarly processed and studied in previous investigations. This was to be expected.

Summary and Conclusions

The effect of increasing the carbon content of the 5Ni steel on the ballistic properties of armor plates with a strong (112) + (111) texture has been investigated. Results indicated that by increasing the carbon content from 0.40 to 0.45 or 0.47 percent, the microstructure and the crystallographic texture of the quenched-and-tempered plate were not significantly affected. The hardness increased slightly, hence the V_{50} ballistic limits increased slightly. The back-spalling and cracking tendencies of the plate upon ballistic impact appeared to be roughly equal to, or slightly poorer than those of the lower carbon (~0.40C) 5Ni plates studied previously. For the higher carbon 5Ni steel, the tempering time at 350°F appeared to influence the hardness and ballistic limit to a greater degree than for the lower carbon 5Ni steels.

Recommendations for Future Work

It is known that the ballistic limit, in general, increases with the hardness of the armor. For steel armor, the hardness can be most effectively increased by increasing the carbon content. However, with increasing carbon content, the sensitivity of the steel to cracking during processing and the tendency for the armor to shatter upon ballistic impact also increase. Moreover, the weldability of the steel generally also deteriorates as the carbon content increases. It is felt, therefore, that future work on the 5Ni textured armor should be directed toward lowering the material and processing cost by decreasing the alloy content without adversely affecting the recrystallization and ferrite formation characteristics during hot working and the high hardenability of the steel.

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Table I

Chemical Composition of the Ni-Cr-Mo and the Mn-Mo-B Armor Steels in Weight Percent

Heat No.	Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Al	B	Ti	Zr	Ce	
8291-8014	Ni-Cr-Mo (high-hardness A-46100B)	0.30	0.92	0.003	0.005	0.43	0.98	0.58	0.50	0.068	-	0.042	0.14	-	(1)
		0.29	0.95	0.002	0.005	0.40	0.94	0.59	0.51	0.078	-	0.038	0.13	-	(3)
8291-8015	Mn-Mo-B (low-hardness A-12560D)	0.28	1.60	0.003	0.005	0.30	0.05	-	0.50	0.050	0.0018	0.029	-	<0.010	(1)
		0.27	1.62	0.001	0.005	0.28	0.048	-	0.50	0.055	0.0007	0.026	-	<0.010	(2)

(1) Ladle analysis
(2) Check analysis on B plates
(3) Check analysis on tempered D plates

Table II

Summary of Microstructural Features, Hardness, and Texture of Isothermally Rolled (80% Reduction) Specimens of the Ni-Cr-Mo Armor Steel (Heat No. 8291-8014)

Rolling Temp., °F (°C)	Microstructural Features	Hardness DPH (Rc)	Texture* $\langle I_{max} \rangle$
1650 (899)	Banded martensite, considerable recrystallization of austenite indicated.	568 (53.5)	4.9
1600 (871)	Banded martensite, some recrystallization of austenite indicated.	571 (53.6)	5.3
1550 (843)	Banded martensite, trace recrystallization of austenite indicated.	575 (53.9)	5.6
1500 (816)	Banded martensite, bands more clearly delineated.	579 (54.1)	5.2
1450 (788)	Banded martensite, trace ferrite formation.	571 (53.6)	5.6
1400 (760)	Banded martensite, ferrite in stringers (~10% in volume).	564 (53.2)	4.8
1350 (732)	Banded martensite, more ferrite in stringers (~25% in volume).	517 (50.3)	5.7

* Texture, (112) + (111) type; $\langle I_{max} \rangle$, averaged intensity maximum in (110) pole figure.

Table III

Summary of Microstructural Features, Hardness, and Texture of Isothermally Rolled (80% Reduction) Specimens of the Mn-Mo-B Armor Steel (Heat No. 8291-8015)

Rolling Temp., °F (°C)	Microstructural Features	Hardness DPH (Rc)	Texture* $\langle I_{max} \rangle$
1650 (899)	Banded martensite, recrystallization of austenite strongly indicated in areas.	575 (53.9)	5.2
1600 (871)	Banded martensite, recrystallization of austenite less strongly indicated.	575 (53.9)	5.3
1550 (843)	Banded martensite, trace of austenite recrystallization.	579 (54.1)	7.2
1500 (816)	Band martensite, no sign of austenite recrystallization.	579 (54.1)	5.8
1450 (788)	Banded martensite, no sign of austenite recrystallization.	575 (53.9)	6.5
1400 (760)	Banded martensite, trace ferrite formation.	575 (53.9)	5.7
1350 (732)	Banded martensite, more ferrite formation (10 to 15% in volume).	543 (51.9)	5.2

* Texture, (112) + (111) type; $\langle I_{max} \rangle$, averaged intensity maximum in (110) pole figure.

Table IV

Summary of Microstructural Features and Hardness of Rolled (70% Reduction at 1550°F) and Isothermally Treated Specimens of the Ni-Cr-Mo Armor Steel (Heat No. 8291-8014)

Isothermal Treatment °F	Sec.	Microstructural Features	Hardness DPH (Rc)
1200	5	Trace ferrite in martensite	547 (52.1)
(649°C)	20	5 to 10 percent ferrite in martensite	533 (51.3)
	60	15 to 20 percent ferrite in martensite	508 (49.7)
	320	~40 percent ferrite in martensite	406 (41.4)
1050	10	Trace ferrite in martensite	547 (52.1)
(566°C)	40	Trace ferrite in martensite	547 (52.1)
	160	Trace ferrite in martensite	547 (52.1)
	640	~3 percent ferrite in martensite	543 (51.9)
900	5	~70 percent bainite,* rest martensite	436 (44.1)
(482°C)	10	75 to 80 percent bainite,* rest martensite	400 (40.8)
	20	~90 percent bainite,* rest martensite	398 (40.6)

* Upper bainite.

Table V

Summary of Microstructural Features and Hardness of Rolled (70% Reduction at 1550°F) and Isothermally Treated Specimens of the Mn-Mo-B Armor Steel (Heat No. 8291-8015)

Isothermal Treatment °F	Isothermal Treatment Sec.	Microstructural Features	Hardness DPH (Rc)
1200	5	Martensite, no ferrite	561 (53.1)
(649°C)	20	Martensite, no ferrite	561 (53.1)
	80	Martensite, no ferrite	561 (53.1)
	320	Martensite, no ferrite	561 (53.1)
1050	10	Martensite, no ferrite	561 (53.1)
(566°C)	40	Martensite, no ferrite	561 (53.1)
	160	Martensite, no ferrite	557 (52.8)
	640	Martensite, no ferrite	561 (53.1)
900	5	~40 percent bainite,* rest martensite	505 (49.5)
(482°C)	10	45 to 50 percent bainite,* rest martensite	511 (49.9)
	20	~70 percent bainite,* rest martensite	444 (44.8)

* Upper bainite.

Table VI

Final Rolling Conditions for Textured Armor Plates of the Ni-Cr-Mo High-Hardness Armor Steel (A-46100B Grade)

Slab ID and Thickness	Final Plate Thickness	Total Reduction
8291-8014-B (1.40 in.)	0.500 in.	64%
8291-8014-C (2.75 in.)	0.250 in.	91%
8291-8014-D (5.50 in.)	0.500 in.	91%

Pass No.	Thickness, inch	Temperature, °F and Time*				Separating Force 10^5 lb.	
		Plate B-1	Sec.	Plate B-2	Sec.	B-1	B-2
0	1.400	1570**	0.0	1600	0.0	0.0	0.0
1	1.246	1500	80.0	1570	58.5	2.9	2.7
2	1.109	1490	87.5	1560	67.0	3.2	2.8
3	0.987	1480	96.0	1550	73.5	3.8	2.8
4	0.878	1470	103.0	1540	81.0	3.5	2.9
5	0.782	1455	109.5	1530	87.0	3.6	2.8
6	0.696	1445	118.0	1515	92.5	3.5	2.8
7	0.619	1425	125.0	1495	99.0	3.4	3.0
8	0.551	1405	131.5	1480	106.0	3.5	3.0
9	0.500	1380	138.5	1450	113.5	3.2	2.7
Quench	-	1310	-	1380	-	-	-
		Plate C-1	Sec.	Plate C-2	Sec.	C-1	C-2
0	2.750	1710**	0.0	1770	0.0	0.0	0.0
1	2.338	1605	161.0	1605	190.0	3.8	4.5
2	1.987	1585	179.5	1585	211.5	4.8	5.3
3	1.689	1575	200.5	1565	231.5	4.9	5.5
4	1.436	1565	211.0	1560	244.0	5.0	5.5
5	1.220	1560	219.0	1550	254.5	4.8	5.2
6	1.037	1555	226.0	1545	262.7	5.1	5.5
7	0.882	1550	233.0	1535	269.0	4.8	4.7
8	0.749	1535	239.0	1520	275.0	4.2	4.8
9	0.637	1520	244.0	1505	280.8	4.3	4.9
10	0.541	1500	250.5	1485	286.4	4.6	5.0
11	0.460	1470	256.5	1455	291.8	4.7	4.8
12	0.391	1445	261.5	1430	297.8	4.7	4.7
13	0.332	1390	268.0	1385	303.0	5.2	4.9
14	0.283	1350	275.0	1345	310.5	5.6	5.6
15	0.250	1310	283.5	1290	318.5	5.4	5.6
Quench	-	-***	-	1220	-	-	-

(Continued)

Table VI (Continued)

Pass No.	Thickness, inch	Temperature, °F and Time*				Separating Force 10^5 lb.	
		Plate D-1	Sec.	Plate D-2	Sec.	D-1	D-2
0	5.500	1770**	0.0	1755	0.0	0.0	0.0
1	4.840	1615	262.0	1600	211.0	4.5	4.5
2	4.259	1595	296.0	1590	288.0	4.5	5.4
3	3.748	1570	331.0	1575	255.5	4.8	5.6
4	3.298	1560	353.0	1565	273.0	5.2	5.6
5	2.903	1550	372.0	1560	288.0	5.6	5.6
6	2.554	1550	387.0	1560	299.0	5.6	5.6
7	2.248	1550	400.0	1560	311.0	5.4	5.0
8	1.978	1550	410.5	1560	321.0	5.2	5.1
9	1.741	1545	421.0	1560	330.0	5.0	4.8
10	1.532	1540	430.5	1560	338.0	4.8	4.8
11	1.348	1515	439.5	1555	345.0	4.7	4.8
12	1.186	1500	447.0	1550	352.0	4.7	4.6
13	1.044	1490	452.0	1540	358.0	4.2	4.2
14	0.919	1470	460.0	1535	364.0	5.1	4.2
15	0.808	1460	467.0	1500	370.0	4.2	4.2
16	0.711	1440	472.5	1490	375.0	4.2	4.4
17	0.626	1420	481.0	1470	382.0	4.4	4.2
18	0.551	1400	489.0	1440	386.0	4.4	3.6
19	0.500	1360	499.5	1380	397.0	3.8	4.2
Quench	-	-***	-	1320	-	-	-

Reduction per pass: 11 percent for B plates.
15 percent for C plates.
12 percent for D plates.

* Time from slab out of furnace.

** Temperature of the slab after discharging from the furnace, moving to the front of the rolling mill, and inserting the thermocouple into the hole.

*** Thermocouple failed.

Table VII

Final Rolling Conditions for Textured Armor Plates of the Mn-Mo-B Low-Hardness Armor Steel (A-12560D Grade)

Slab ID and Thickness	Final Plate Thickness	Total Reduction
8291-8015-B (1.40 in.)	0.500 in.	64%
8291-8015-C (2.75 in.)	0.250 in.	91%
8291-8015-D (5.50 in.)	0.500 in.	91%

Pass No.	Thickness, inch	Temperature, °F and Time*				Separating Force 10^5 lb.	
		Plate B-1	Sec.	Plate B-2	Sec.	B-1	B-2
0	1.400	1625**	0.0	1600	0.0	0.0	0.0
1	1.246	1600	58.0	1580	58.0	2.6	2.6
2	1.109	1580	71.0	1570	69.5	2.8	2.8
3	0.987	1560	82.0	1550	79.0	2.9	2.9
4	0.878	1545	92.0	1535	89.0	3.0	3.0
5	0.782	1535	98.5	1520	96.5	2.9	2.9
6	0.696	1525	105.0	1510	102.5	3.0	2.9
7	0.619	1510	111.0	1490	108.0	2.9	2.9
8	0.551	1490	117.5	1470	115.0	3.2	3.1
9	0.500	1455	125.0	1445	1220	2.9	2.8
Quench	-	1370	-	1400	-	-	-
		Plate C-1	Sec.	Plate C-2	Sec.	C-1	C-2
0	2.750	1760**	0.0	1770	0.0	0.0	0.0
1	2.338	1600	176.0	1605	174.5	4.4	4.4
2	1.987	1585	199.5	1585	195.0	4.8	4.6
3	1.689	1565	219.0	1570	216.0	5.0	5.0
4	1.436	1565	229.5	1560	228.0	4.4	4.8
5	1.220	1555	239.0	1560	237.5	4.7	4.7
6	1.037	1550	247.0	1545	247.0	4.6	4.6
7	0.882	1540	254.5	1535	254.0	4.6	4.6
8	0.749	1525	262.0	1515	263.0	4.6	4.4
9	0.637	1505	269.0	1480	269.0	4.4	4.3
10	0.541	1485	274.0	1465	275.5	4.6	4.5
11	0.460	1455	281.0	1420	282.0	4.8	4.6
12	0.391	1430	287.5	1405	288.5	4.6	4.5
13	0.332	1390	293.5	1370	295.0	4.8	4.6
14	0.283	1350	300.0	1340	302.0	4.6	4.8
15	0.250	1300	307.5	1275	313.5	5.0	5.0
Quench	-	1240	-	1190	-	-	-

(Continued)

Table VII (Continued)

Pass No.	Thickness, inch	Temperature, °F and Time* Plate D-1	Sec.	Plate D-2	Sec.	Separating Force 10^5 lb. D-1	D-2
0	5.500	1800**	0.0	1790	0.0	0.0	0.0
1	4.840	1610	315.0	1610	313.0	5.6	5.4
2	4.259	1590	349.0	1590	345.0	6.4	6.0
3	3.748	1570	382.0	1570	378.0	6.4	6.0
4	3.298	1560	406.5	1565	400.0	6.4	6.1
5	2.903	1560	419.0	1565	414.5	6.2	5.8
6	2.554	1560	434.0	1565	428.0	5.9	5.6
7	2.248	1560	444.5	1560	443.5	5.7	5.4
8	1.978	1560	456.0	1560	455.0	5.5	5.4
9	1.741	1555	466.0	1560	465.5	5.4	4.9
10	1.532	1550	474.0	1555	475.0	5.2	5.3
11	1.348	1550	480.0	1530	482.5	5.0	4.8
12	1.186	1535	489.0	1490	492.0	5.4	4.8
13	1.044	1520	496.5	1500	496.0	5.2	3.8
14	0.919	1490	503.0	1490	504.0	4.8	5.2
15	0.808	1470	509.5	1470	511.0	4.4	4.2
16	0.711	1450	517.0	1440	517.0	4.2	4.0
17	0.626	1420	523.0	1430	523.0	4.4	3.8
18	0.551	1410	529.0	1410	529.5	4.4	4.4
19	0.500	1370	537.0	1380	538.0	4.0	3.8
Quench	-	1280	-	1320	-	-	-

Reduction per pass: 11 percent for B plates.
15 percent for C plates.
12 percent for D plates.

* Time from slab out of the furnace.

** Temperature of the slab after discharging from the furnace, moving to the front of the rolling mill, and inserting thermocouple into the hole.

Table VIII

Hardness of the Ni-Cr-Mo and Mn-Mo-B Armor Plates

Ni-Cr-Mo Steel (8291-8014) Plate No.	As-Quenched		Tempered 350°F - 1 hour	
	DPH	HRC	DPH	HRC
B1	558	52.9	549	52.2
B2	559	52.9	543	51.9
C1	508	49.7	489	48.3
C2	494	48.7	490	48.4
D1	539	51.7	543	51.9
D2	554	52.6	543	51.9

Mn-Mo-B Steel (8291-8015) Plate No.	As-Quenched		Tempered 1100°F - 1 hour	
	DPH	HRC	DPH	HRC
B1	547	52.1	362	35.7
B2	553	52.5	353	35.9
C1	558	52.9	359	36.5
C2	566	5303	359	36.5
D1	563	53.2	360	36.6
D2	554	52.6	360	36.6

Table IX

Microstructural Features of the Plates

Steel and Plate	Microstructural Features
Ni-Cr-Mo: Tempered 350°F 1 hour (8291-8014)	
B1	Banded martensite, coarse bands, some ferrite
B2	Banded martensite, coarse bands, some ferrite
C1	Banded martensite, fine bands, appreciable ferrite (10 to 15%)
C2	Banded martensite, fine bands, appreciable ferrite
D1	Banded martensite, fine bands, some ferrite
D2	Banded martensite, fine bands, some ferrite
Mn-Mo-B: Tempered 1100°F 1 hour (8291-8015)	
B1	Banded martensite, coarse bands, no ferrite
B2	Banded martensite, coarse bands, no ferrite
C1	Banded martensite, fine bands, trace ferrite
C2	Banded martensite, fine bands, trace ferrite
D1	Banded martensite, fine bands, trace ferrite
D2	Banded martensite, fine bands, trace ferrite

Table X

Summary of Texture Intensities
Observed at Midthickness of the Plates

Steel and Plate	$\langle I_{max} \rangle$,* Random Units
Ni-Cr-Mo (8291-8014)	
B1	4.3
B2	4.9
C1	7.1
C2	6.1
D1	6.2
D2	4.9
Mn-Mo-B (8291-8015)	
B1	4.7
B2	4.1
C1	9.3
C2	8.8
D1	8.1
D2	6.9

* From the (110) pole figures.

Table XI

Tensile Properties of Tempered Plates of the Ni-Cr-Mo and Mn-Mo-B Armor Steels

Steel and Plate Designation	0.2% Yield Strength, ksi (MPa) L	D	T	Tensile Strength, ksi (MPa) L	D	T	Reduction of Area, % L	D	T	Total Elong., % L	D	T
Ni-Cr-Mo: Tempered 350°F 1 hour (8291-8014)												
B2	223.0 (1538)	232.6 (1604)	233.4 (1609)	260.6 (1797)	268.6 (1852)	275.9 (1902)	51.0	47.3	30.6	12.0	11.0	8.5
	T/L	1.047			1.059			0.600			0.708	
C2	230.0 (1586)	229.0 (1579)	239.3 (1650)	260.2 (1794)	261.1 (1800)	272.7 (1880)	46.1	45.7	35.1	12.0	13.0	8.0
	T/L	1.040			1.048			0.761			0.667	
D2	234.1 (1614)	232.4 (1602)	243.9 (1682)	264.4 (1823)	263.7 (1818)	275.7 (1901)	49.0	45.0	35.2	12.0	11.0	9.0
	T/L	1.042			1.043			0.718			0.750	
Mn-Mo-B: Tempered 1100°F 1 hour (8291-8015)												
B2	-	153.6 (1059)	157.0 (1083)	152.4 (1051)	159.4 (1099)	162.7 (1122)	68.0	64.1	53.3	19.0	18.0	15.0
	T/L	-			1.068			0.784			0.789	
C2	154.9 (1068)	168.0 (1158)	159.9 (1102)	159.0 (1097)	170.4 (1175)	163.7 (1129)	63.3	53.4	57.9	21.0	18.0	14.0
	T/L	1.032			1.029			0.915			0.667	

Results represent the averaged values of duplicate specimens tested for each plate.
Plates B and D, 1/2 inch thick; C, 1/4 inch thick.

Table XII

Through-Thickness Tensile Properties of Notched Specimens of the Ni-Cr-Mo and Mn-Mo-B Armor Plates

Steel and Plate Designation	Hardness of Plate, HRC	Tensile Strength, ksi (MPa)	Total Elongation, pct.
Ni-Cr-Mo: Tempered 350°F 1 hour (8291-8014)			
B2	51.9	324.1 (2235)	0.37
D2	51.9	316.9 (2185)	0.42
Mn-Mo-B: Tempered 1100°F 1 hour (8291-8015)			
B2	35.9	231.6 (1597)	1.11
D2	36.6	233.7 (1611)	0.95

Results represent averaged values of duplicate specimens tested for each plate. Thickness of Plates B and D, 1/2 inch (minimum thickness for this test).

Table XIII

Charpy V-Notch Impact Properties of Tempered Plates of the Ni-Cr-Mo and Mn-Mo-B Armor Steels

Steel and Plate Designation	Impact Energy L ft-lb	(J)	D ft-lb	(J)	T ft-lb	(J)	Hardness of Plate, HRC
Ni-Cr-Mo: Tempered 350°F 1 hour (8291-8014)							
B2	14.3	(19.4)	13.0	(17.6)	9.0	(12.2)	51.9
C2 Actual	9.3	(12.6)	8.0	(10.8)	-	-	48.4
C2 Converted	18.6	(25.2)	16.0	(21.6)	-	-	46.4
D2	14.5	(19.7)	13.8	(18.7)	9.4	(12.7)	51.9
Mn-Mo-B: Tempered 1100°F 1 hour (8291-8015)							
B2	70.5	(95.6)	57.8	(78.4)	30.6	(41.5)	35.9
C2 Actual	24.7	(33.5)	24.0	(32.5)	13.3	(18.0)	36.5
C2 Converted	59.4	(67.0)	48.0	(65.0)	26.6	(36.0)	36.5
D2	68.5	(92.9)	62.5	(84.7)	30.0	(40.7)	36.6

Plates B and D, 1/2 inch thick, full-size specimens tested; Plate C, 1/4 inch thick, half-size specimens tested and converted according to Reference 17 (2 X actual).

Results represent averaged values of duplicate specimens tested for each plate.

Table XIV

Ballistic Performance of
Ni-Cr-Mo and Mn-Mo-B Armor Plates

Steel and Plate Designation	Rolling Reduction, %	Texture Intensity, $\langle I_{max} \rangle$	Tempering Treatment, 1 hou[illegible] 350°F (177°C) Thick., in.*	HRC	V_{50}, fps	1100 [illegible]93°C) Thick., in.*	HRC	V_{50}, fps
Ni-Cr-Mo (8291-8014)								
B1	60	4.3	0.485	49	1740	0.481	38	1828
B2		4.9	0.477	51	2075	0.477	37	1650
C1	90	7.1	0.262	50	1902	0.258	33	1573
C2		6.1	0.260	49	1792	0.263	36	1650
D1	90	6.2	0.496	50	1355	0.496	37	1818
D2		4.9	0.499	44	1443	0.501	38	1845
Mn-Mo-B (8291-8015)								
B1	60	4.7	0.480	49	1374	0.484	38	1732
B2		4.1	0.482	51	1270	0.480	40	1772
C1	90	9.3	0.260	52	1414	0.255	37	1584
C2		8.8	0.258	49	2042	0.259	36	1505
D1	90	8.1	0.499	52	1267	0.497	42	1857
D2		6.9	0.497	52	1930	0.496	37	1782

* Plate thickness includes ~0.020-inch oxide and decarburized layers. For plates ~1/2 inch thick, 0.50 caliber AP M2 projectiles were used; for plate ~1/4 inch thick, 0.30 caliber AP M2 projectiles were used. All tested at 0° obliquity.

Table XV

Ballistic Performance of Selected Plates
Surface Ground or Grit Blasted Before Testing

Steel and Plate Designation	Rolling Reduction, %	Tempering Treatment 1 hour at	Test Plate Thickness, inch	Test Plate Hardness, HRC	Ballistic Limit V_{50}, fps
Ni-Cr-Mo (8291-8014)					
B1	60	350°F	0.478	51	1677
C1	90	350°F	0.257	51	2039
D1	90	350°F	0.457*	52	1792
Mn-Mo-B (8291-8015)					
C1	90	1100°F	0.260	38	1647
C2			0.261	37	1630
D1	90	1100°F	0.459*	37	1560
D2			0.497	38	1824

* Thickness after surface grinding. All other plates had some curvature and were grit blasted to remove surface scale.

Table XVI

Ballistic Limits of Ni-Cr-Mo Armor Plates

Steel and Plate Designation	Test Plate Thickness, inch	Test Plate Hardness, HRC	Test Data CPTP/PP*, fps	Ballistic Limits V_{50}, fps	Remarks
Ni-Cr-Mo Tempered at 350°F 1 hour (8291-8014)					Double V_{50} limits due possibly to Shatter Gap:
B1	0.485	49	2134/2065 1746/1745	2100 1746	Indicated
B2	0.477	51	2122/2070 --	2096 --	Not indicated
C1	0.262	50	1922/1911 --	1917 --	Not indicated
C2	0.260	49	2014/1974 1811/1810	1994 1811	Indicated
D1	0.496	50	1443/1274 --	1313 --	Not indicated
D2	0.499	44	1448/1443 --	1626 --	Not indicated
Ni-Cr-Mo Tempered 1100°F 1 hour (8291-8014)					
B1	0.481	38	1878/1781 --	1830 --	Not indicated
B2	0.477	37	-- 1685/1553	-- 1619	Not indicated
C1	0.258	33	1599/1556 --	1578 --	Not indicated
C2	0.263	36	-- 1670/1649	-- 1660	Not indicated
D1	0.496	37	-- 1876/1781	-- 1829	Not indicated
D2	0.501	38	-- 1891/1810	-- 1851	Not indicated

* CPTP: complete penetration through plate
PP: partial penetration

Table XVII

Ballistic Limits of Mn-Mo-B Armor Plates

Steel and Plate Designation	Test Plate Thickness, inch	Test Plate Hardness, HRC	Test Data CPTP/PP*, fps	Ballistic Limits V_{50}, fps	Remarks
Mn-Mo-B Tempered 1100°F 1 hour (8291-8015)					Double V_{50} limits due possibly to Shatter Gap:
B1	0.484	38	1789/1682 --	1736 --	Not indicated
B2	0.480	40	-- 1804/1751	-- 1778	Not indicated
C1	0.255	37	1589/1568 --	1579 --	Not indicated
C2	0.259	36	-- 1522/1500	-- 1511	Not indicated
D1	0.497	42	-- 1905/1836	-- 1871	Not indicated
D2	0.496	37	-- 1795/1702	-- 1749	Not indicated
Mn-Mo-B Tempered at 350°F 1 hour (8291-8015)					
B1	0.480	49	1399/1357 --	1378 --	Not indicated
B2	0.482	51	1290/1258 -	1274 -	Not indicated
C1	0.260	52	1515/1457 1410/1408	1486 1409	Not indicated
C2	0.258	49	2043/1943 1584/1511	1993 1548	Indicated
D1	0.499	52	1282/1260 --	1271 --	Not indicated
D2	0.497	52	1854/1854 1998/1946	1854 1972	Not indicated

* CPTP: complete penetration through plate
PP: partial penetration

Table XVIII

Chemical Composition of the 5Ni Armor Steel in Weight Percent
(First Heat)

Heat No.	C	Mn	P	S	Si	Cu	Ni	Mo	V	Al	N	
8291-8016	0.47	0.61	0.001	0.006	1.38	1.14	5.65	0.51	0.10	0.067	0.003	(ladle)
			0.002	0.007	(Check 1)*							
			-	0.007	(Check 2)**							

* Sample taken from Slab A near centerline of ingot.
** Sample taken from Slab A near rim of ingot.

Table XIX

Chemical Composition of the 5Ni Armor Steel in Weight Percent
(Second Heat)

Heat No.	C	Mn	P	S	Si	Cu	Ni	Mo	V	Al	N	
8291-8019	0.45	0.60	0.001	0.002	1.30	1.07	5.44	0.48	0.10	0.055	0.004	(ladle)

Table XX

Final Rolling Conditions for Textured Armor Plates of the 5Ni Steel with 0.45 Percent Carbon

Slab ID and Thickness	Final Plate Thickness	Total Reduction
8291-8019 A (1.40 in.)	0.500 in.	64%
8291-8019 B (2.75 in.)	0.250 in.	91%
8291-8019 C (5.50 in.)	0.500 in.	91%

Pass No.	Thickness, inch	Temperature, °F Time,*** (sec.) Plate A-1		Plate A-2		Separating Force,* 10^5 lb
0	1.400	1680	(113)	1720	(135)	-
1	1.246	1560		1560		3.20
2	1.109	1530	(125)	1540	(149)	3.50
3	0.987	1520	(137)	1530	(161)	3.70
4	0.878	1510	(145)	1510	(173)	3.70
5	0.782	1505	(152)	1500	(183)	3.60
6	0.696	1490	(159)	1490	(191)	3.65
7	0.619	1480	(166)	1470	(201)	3.90
8	0.551	1470	(174)	1460	(207)	3.95
9	0.500	1440	(183)	1440	(214)	3.75
Quench	-	1380	-	1360	-	-
		Plate B-1		Plate B-2		
0	2.750	1770	(195)	1770	(205)	-
1	2.338	1600		1600		5.20
2	1.987	1595	(213)	1580	(228)	5.90
3	1.689	1590	(229)	1570	(245)	6.00
4	1.436	1580	(242)	1560	(261)	5.90
5	1.220	1565	(258)	1560	(275)	5.90
6	1.037	1550	(272)	1550	(286)	5.60
7	0.882	1550	(282)	1550	(295)	5.60
8	0.749	1540	(290)	1550	(300)	5.30
9	0.637	1530	(298)	1510	(308)	6.15
10	0.541	1520	(306)	1510	(314)	5.41
11	0.460	1490	(314)	1490	(321)	5.60
12	0.391	1470	(320)	1460	(327)	5.00
13	0.332	1440	(328)	1420	(333)	6.00
14	0.283	1400	(334)	1390	(340)	5.70
15	0.250	-**	(343)	1360	(348)	5.80
Quench	-	-	-	1300	-	-

(Continued)

Table XX (Continued)

Pass No.	Thickness, inch	Temperature, °F Time,*** (sec.) Plate C-1		Plate C-2		Separating Force,* 10^5 lb
0	5.500	1660	(233)	1625	(163)	-
1	4.840	1590		1600		6.00
2	4.259	1570	(266)	1570	(203)	6.50
3	3.748	1565	(296)	1560	(242)	6.50
4	3.298	1560	(316)	1550	(269)	6.40
5	2.903	1550	(338)	1540	(297)	6.30
6	2.554	1550	(353)	1540	(317)	6.00
7	2.248	1540	(374)	1530	(334)	5.90
8	1.978	1540	(391)	1530	(348)	6.65
9	1.741	1520	(413)	1520	(363)	6.80
10	1.532	1510	(426)	1515	(378)	6.00
11	1.348	1500	(435)	1500	(390)	6.00
12	1.186	1490	(443)	1500	(400)	5.80
13	1.044	1480	(451)	1490	(409)	5.60
14	0.919	1470	(457)	1485	(415)	5.10
15	0.808	1445	(467)	1470	(422)	6.20
16	0.711	1430	(477)	1455	(429)	5.40
17	0.626	-**	(487)	1440	(438)	5.10
18	0.551	-**	(494)	1435	(444)	5.20
19	0.500	-**	(500)	1400	(454)	4.70
Quench	-	-	-	1370	-	-

* Separating forces shown from the No. 1 plates only, data for the No. 2 plates very similar.
Reduction per pass: 11% for A plates
15% for B plates
12% for C plates

** Thermocouple failed.

*** Time from slab out of furnace to entry of the first pass.

Table XXI

Final Rolling Conditions for Textured Armor of the 0.47C, 5Ni Armor Steel

Slab ID and Thickness	Final Plate Thickness	Total Rejection
8291-8016-A (1.40 in.)	0.50 in.	64%
B (2.75 in.)	0.25 in.	91%
C (5.50 in.)	0.50 in.	91%

Pass No.	Thickness, in.	Temperature, °F	Time,* sec.	Separating Force, 10^5 lb
		Plate A-1		
0	1.400	1610	0.0	0.0
1	1.246	1570	42.5	2.6
2	1.109	1555	52.5	3.2
3	0.987	1540	61.5	3.2
4	0.878	1515	71.0	3.3
5	0.782	1500	78.0	3.4
6	0.696	1490	85.0	3.4
7	0.619	1465	92.0	3.6
8	0.551	1450	98.5	3.6
9	0.500	1410	105.5	3.4
Quench	-	1340	-	-
		Plate B-1		
0	2.750	1760	0.0	0.0
1	2.338	1600	190.0	4.2
2	1.987	1585	202.0	5.0
3	1.689	1570	219.0	5.0
4	1.436	1570	231.0	5.2
5	1.220	1560	244.5	4.8
6	1.037	1550	254.5	4.6
7	0.882	1540	263.5	4.5
8	0.749	1530	272.0	4.2
9	0.637	1515	279.0	4.2
10	0.541	1490	285.0	4.3
11	0.460	1460	293.0	4.6
12	0.391	1440	299.0	4.5
13	0.332	1340	309.0	4.8
14	0.283	1310	321.0	5.2
15	0.250	1270	328.5	5.4
Quench	-	1200	-	-

(Continued)

Table XXI (Continued)

Pass No.	Thickness, in.	Temperature, °F Plate A-1	Time,* sec.	Separating Force, 10^5 lb
0	5.500	1765	0.0	0.0
1	4.840	1600	303.0	5.7
2	4.259	1590	329.0	6.6
3	3.748	1570	363.0	5.8
4	3.298	1570	383.5	6.2
5	2.903	1560	407.0	6.4
6	2.554	1560	428.0	6.2
7	2.248	1550	446.0	6.0
8	1.978	1550	461.5	6.4
9	1.741	1545	474.5	5.6
10	1.532	1525	483.0	5.6
11	1.348	1490	495.0	5.2
12	1.186	1490	505.0	5.0
13	1.044	1480	514.0	4.8
14	0.919	1450	521.0	4.4
15	0.808	1460	528.5	4.4
16	0.711	1440	534.0	4.2
17	0.626	1410	542.0	4.2
18	0.551	1420	548.5	4.1
19	0.500	1390	557.0	4.1
Quench	-	1350	-	-

Reduction per pass: 11% for A plates.
15% for B plates.
12% for C plates.

* Time from slab out of furnace to entry of the first pass.

Table XXII

Ballistic Examination of Textured Armor Plates of the 0.45C, 5Ni Armor Steel

Steel and Plate Designation	Rolling Reduction, %	Texture** Intensity, $\langle I_{max} \rangle$	Thickness* Test Plate, inch	Hardness Test Plate, HRC	Caliber, AP M2 Projectile; at 0° Obliquity
0.45C, 5Ni On-Line Tempered 350°F for ~1 hour (8291-8019)					
A1	60	4.3	0.486	56	0.50
A2		4.3	0.490	57	
B1	90	6.7	0.271	53	0.30
B2		6.3	0.270	56	
C1	90	6.1	0.506	56	0.50
C2		7.2	0.501	57	

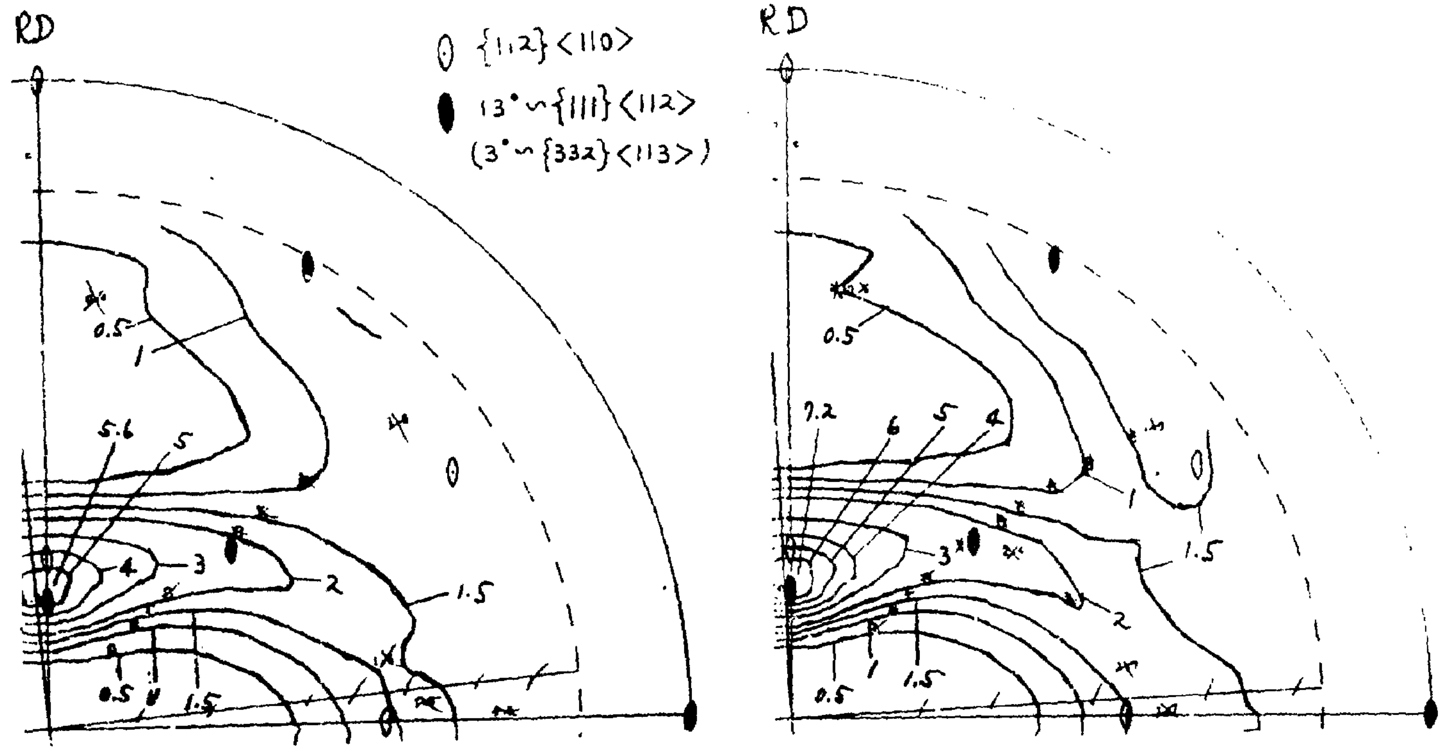
* Includes ~0.020-inch-thick surface oxide and decarburized layers.
** Texture, (112) + (111) type; $\langle I_{max} \rangle$, average intensity maxima in (110) pole figure.

Table XXIII

Ballistic Examination of Textured Armor Plates of the Higher Carbon 5Ni Steels

Steel and Plate Designation	Rolling Reduction, %	Texture Intensity, $\langle I_{max} \rangle$	Thickness* Test Plate, inch	Hardness Test Plate, HRC	Caliber, AP M2 Projectile; at 0° Obliquity
0.45C, 5Ni Tempered 350°F 1 hour** (8291-8019)					
A1	60	4.3	0.488	53	0.50
A2		4.3	0.496	54	
B1	90	6.7	0.266	54	0.30
B2		6.3	0.265	54	
C1	90	6.1	0.506	54	0.50
C2		7.2	0.502	54	
0.47C, 5Ni Tempered 350°F 1 hour (8291-8016)					
A1	60	4.0	0.480	55	0.50
			0.479	57	
B1	90	7.1	0.268	57	0.30
			0.267	58	
C1	90	6.1	0.501	56	0.50
			0.498	56	

* Includes ~0.020-inch-thick surface oxide and decarburized layers.
** Additional to on-line tempering treatment (350°F ~1 hr.) immediately after quenching.



(A) Ni-Cr-Mo

(B) Mn-Mo-B

Figure 1. (110) POLE FIGURES SHOWING TEXTURE OF STEELS ISOTHERMALLY ROLLED AT 1550°F (843°C) TO 80 PERCENT REDUCTION AND IMMEDIATELY QUENCHED.

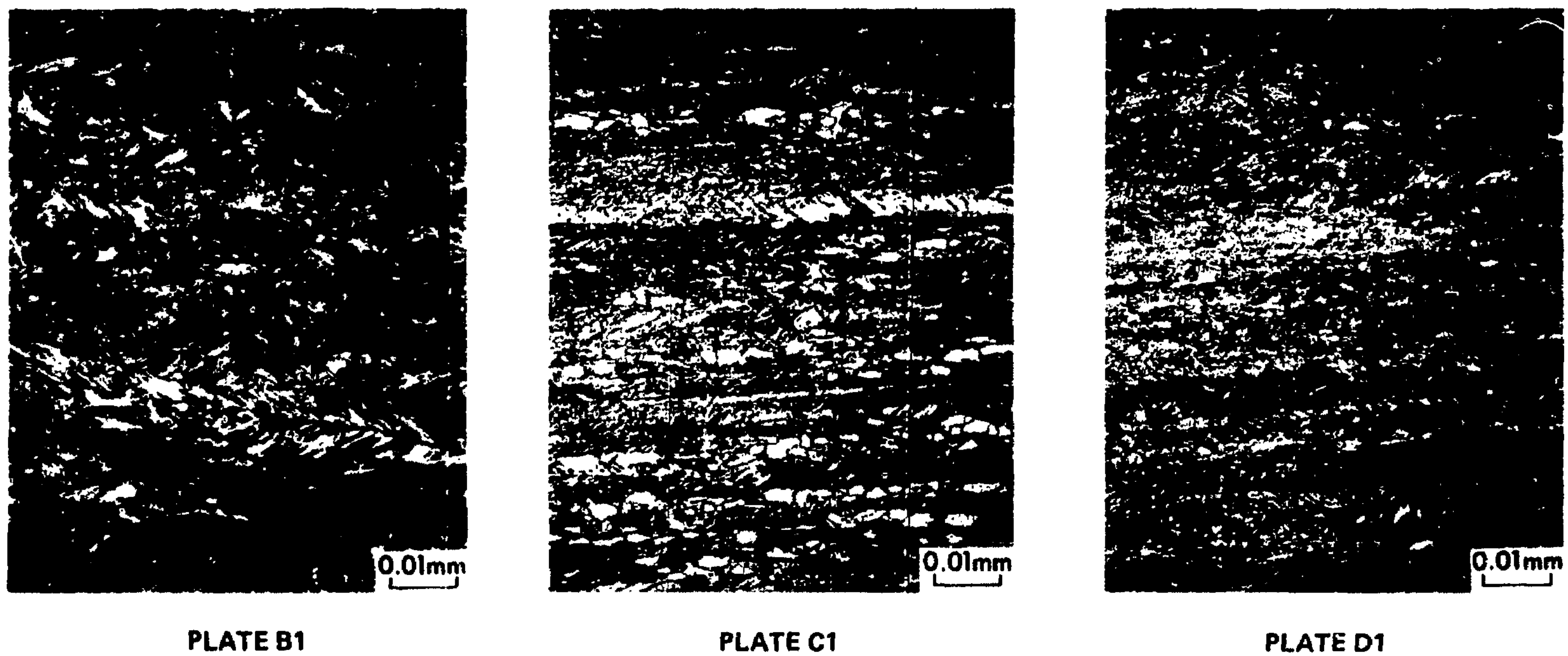


Figure 2. MICROSTRUCTURE OF Ni-Cr-Mo STEEL PLATES TEMPERED AT 350°F FOR 1 HOUR. LONGITUDINAL SECTION. NITAL ETCH. 1000X.

PLATE B1

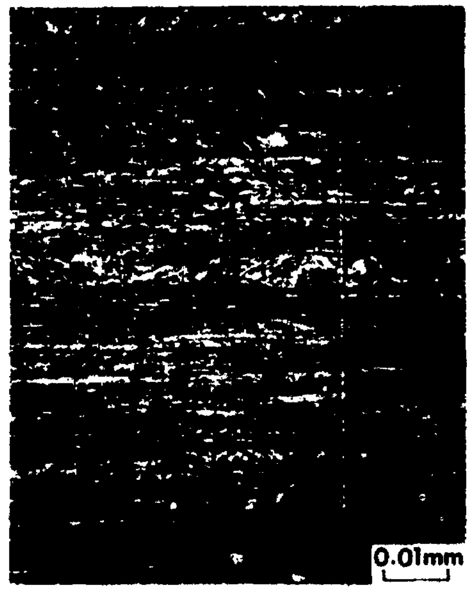


PLATE C1

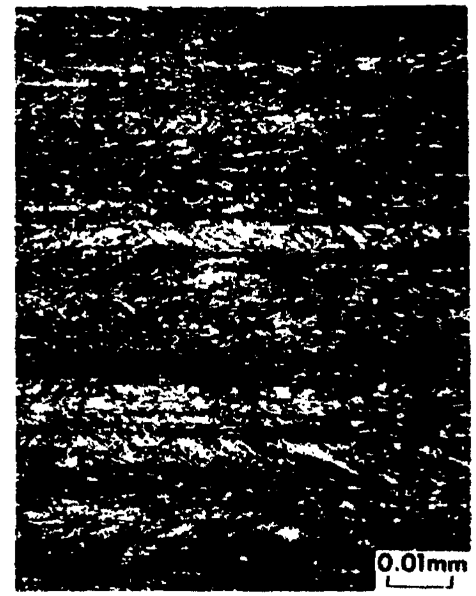
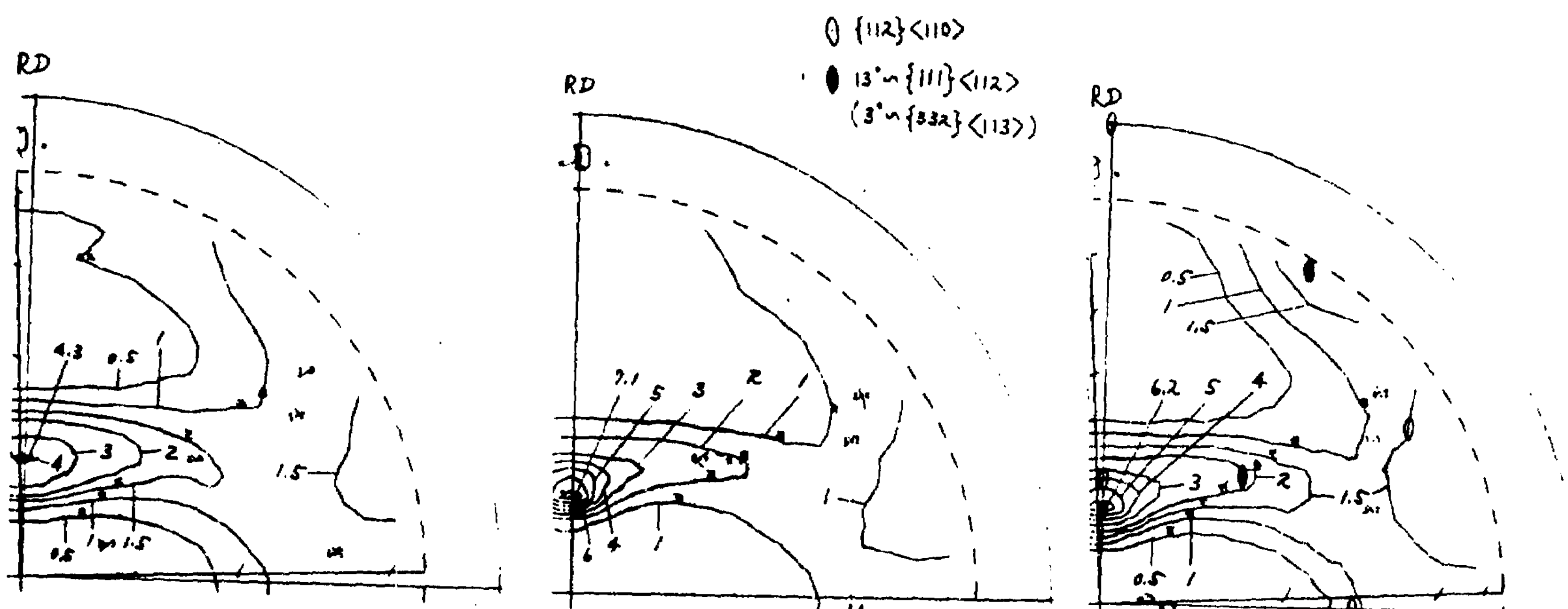


PLATE D1

Figure 3. MICROSTRUCTURE OF Mn-Mo-B STEEL PLATES TEMPERED AT 1100°F FOR 1 HOUR. LONGITUDINAL SECTION. NITAL ETCH. 1000X.

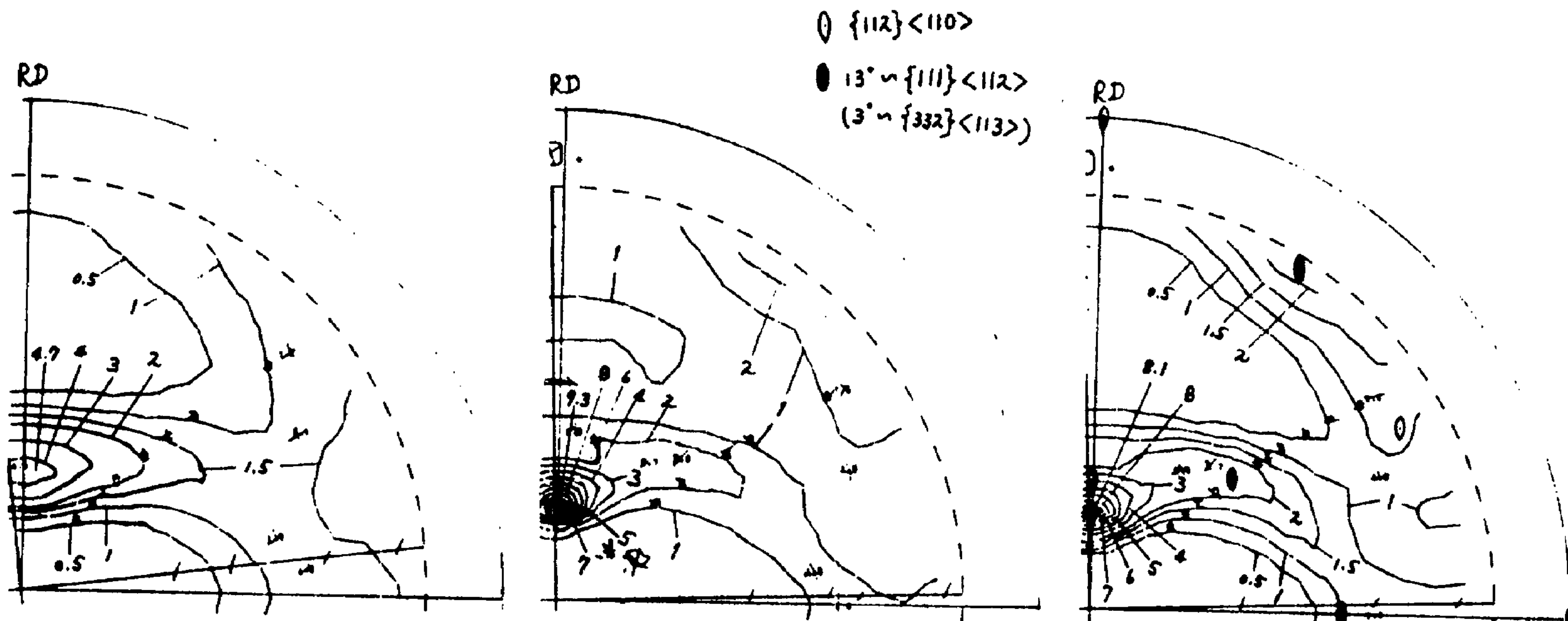


(A) PLATE B1 (ROLLED 60% TO 0.50 IN. THICK)

(B) PLATE C1 (ROLLED 90% TO 0.25 IN. THICK)

(C) PLATE D1 (ROLLED 90% TO 0.50 IN. THICK)

Figure 4. (110) POLE FIGURES SHOWING TEXTURE OF THE VARIOUS PLATES OF THE Ni-Cr-Mo STEEL, ROLLED, IMMEDIATELY QUENCHED, AND SUBSEQUENTLY TEMPERED AT 360°F FOR 1 HOUR.

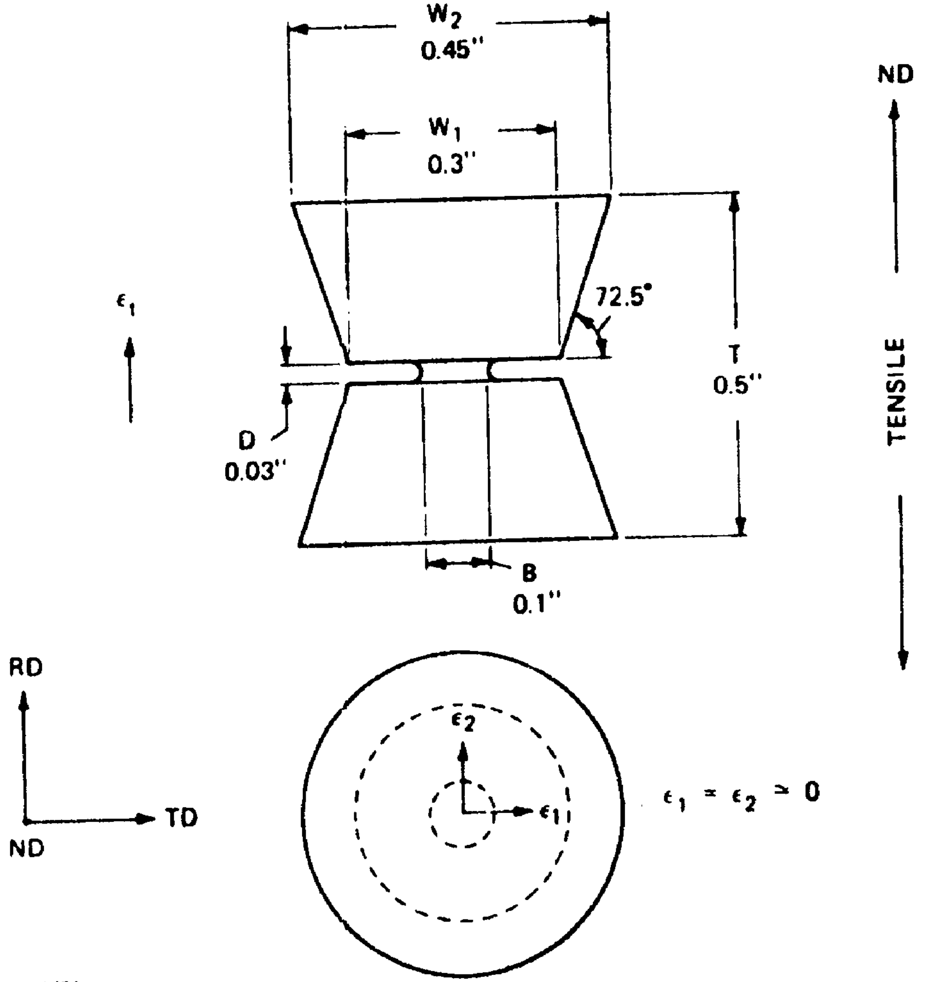


(A) PLATE B1 (ROLLED 60% TO 0.50 IN. THICK)

(B) PLATE C1 (ROLLED 90% TO 0.25 IN. THICK)

(C) PLATE D1 (ROLLED 90% TO 0.50 IN. THICK)

Figure 5. (110) POLE FIGURES SHOWING TEXTURE OF THE VARIOUS PLATES OF THE Mn-Mo-B STEEL, ROLLED, IMMEDIATELY QUENCHED, AND SUBSEQUENTLY TEMPERED AT 1100°F FOR 1 HOUR.



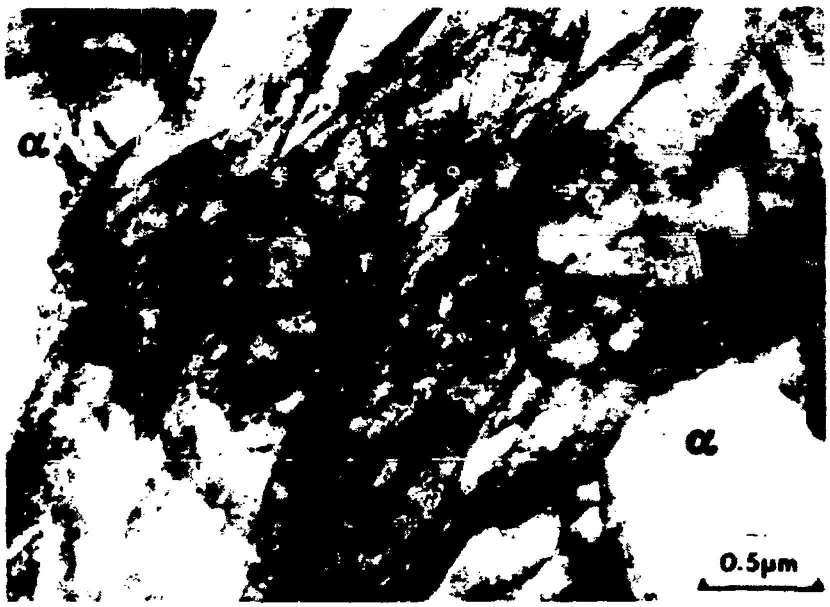
(B = W/3, D = B/3.3, B = T/5)

SCALE 4:1

1 inch = 25.4 mm

Figure 6. THROUGH-THICKNESS NOTCHED TENSILE SPECIMEN FOR TESTING SPALLING RESISTANCE OF PLATE (STRAIN RATE CONSTANT).

(A)



(B)

Figure 7. TRANSMISSION ELECTRON MICROGRAPHS SHOWING SUB-STRUCTURE OF PLATE D1 OF Ni-Cr-Mo STEEL IN THE AS-QUENCHED CONDITION. LONGITUDINAL SECTION.

(A)

(B)

Figure 8. TRANSMISSION ELECTRON MICROGRAPHS SHOWING SUBSTRUCTURE OF PLATE D1 OF Mn-Mo-B STEEL IN THE AS-QUENCHED CONDITION. LONGITUDINAL SECTION.

(A) Ni-Cr-Mo PLATE D1 AS-QUENCHED

(B) Mn-Mo-B PLATE D1 TEMPERED 350°F - 1 HOUR (DARK FIELD IMAGE USING ϵ-CARBIDE REFLECTION)

Figure 9. TRANSMISSION ELECTRON MICROGRAPHS SHOWING PRESENCE OF EPSILON-CARBIDE PRECIPITATES.

(A)

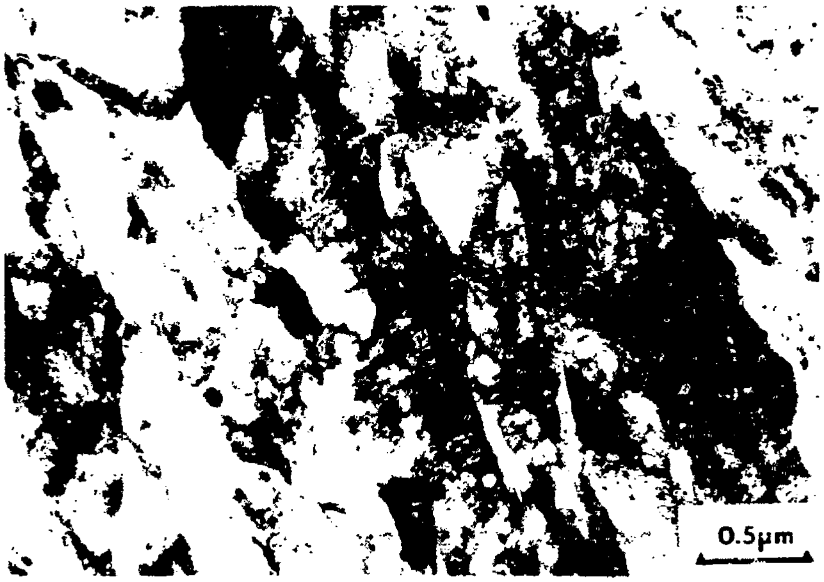
(B)

Figure 10. TRANSMISSION ELECTRON MICROGRAPHS SHOWING SUBSTRUCTURE OF PLATE D1 OF Ni-Cr-Mo STEEL AFTER TEMPERING AT 350°F FOR 1 HOUR. LONGITUDINAL SECTION.

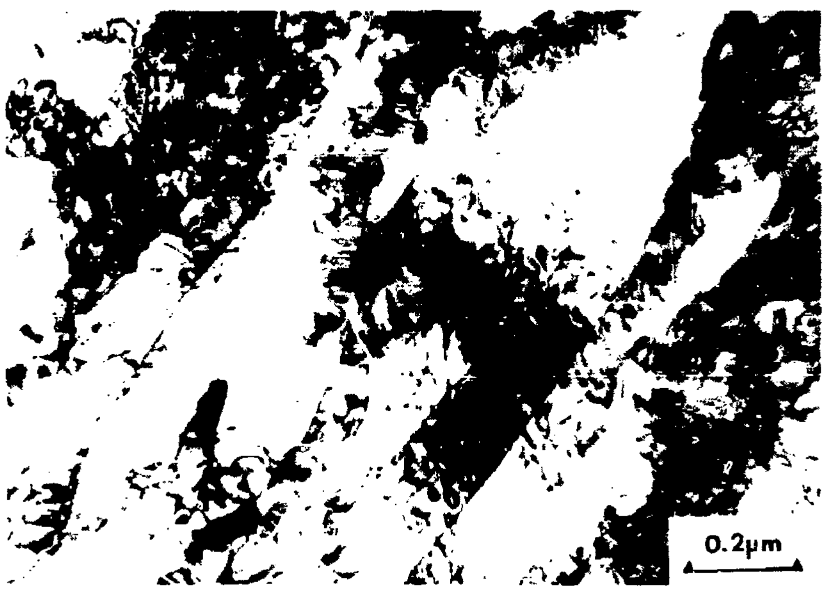
(A)

(B)

Figure 11. TRANSMISSION ELECTRON MICROGRAPHS SHOWING SUBSTRUCTURE OF PLATE D1 OF Mn-Mo-B STEEL AFTER TEMPERING AT 360° FOR 1 HOUR. LONGITUDINAL SECTION.

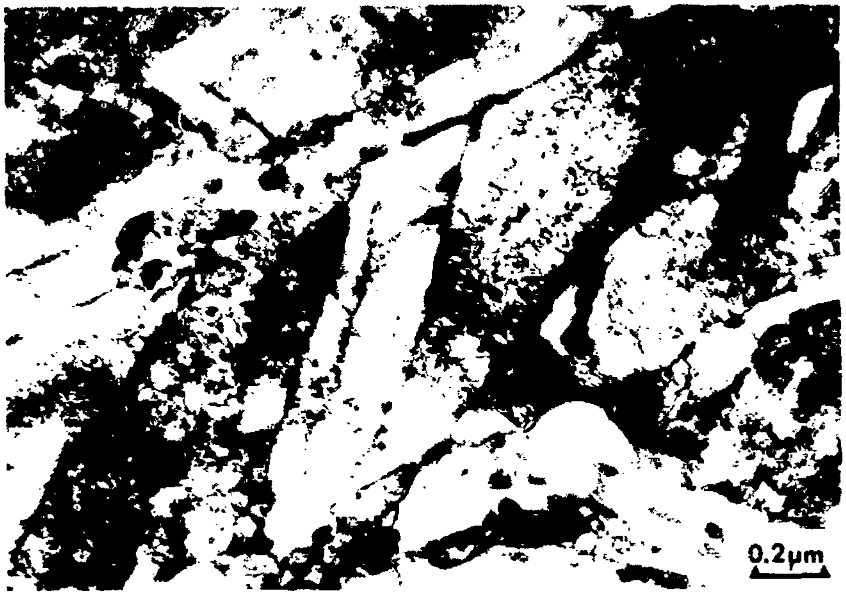


(A)



(B)

Figure 12. TRANSMISSION ELECTRON MICROGRAPHS SHOWING SUBSTRUCTURE OF PLATE D1 OF Ni-Cr-Mo STEEL AFTER TEMPERING AT 1100°F FOR 1 HOUR. LONGITUDINAL SECTION.



(A)

(B)

Figure 13. TRANSMISSION ELECTRON MICROGRAPHS SHOWING SUB-STRUCTURE OF PLATE D1 OF Mn-Mo-B STEEL AFTER TEMPERING AT 1100°F FOR 1 HOUR. LONGITUDINAL SECTION.

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Results indicated that a strong (112)+(111) texture could be produced in plates of both armor steels. Because of the relatively low hardenabilities of these steels, particularly the Ni-Cr-Mo steel, ferrite formation could not be prevented in the on-line quenched plates. The ballistic test results were widely scattered. For optimum development of the (112)+(111) texture in the martensite, studies involving nearly isothermal rolling at a suitable temperature are recommended.

The effect of increasing carbon of the 5Ni steel to 0.45 or 0.47 percent was to increase slightly the hardness and the V_{50} ballistic limit of the textured armor plates. With the higher carbon content, the tempering time appeared to influence the hardness and the ballistic limit to a greater degree than for the lower carbon 5Ni steel. Studies aimed at lowering the alloy content of the 5Ni steels are recommended.

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Hsun Hu
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